

BOOSTED DARK MATTER SIGNALS ENHANCED WITH SELF- INTERACTIONS

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based on Phys. Lett. B 743(2015) 256-266 with K. Kong and JC Park

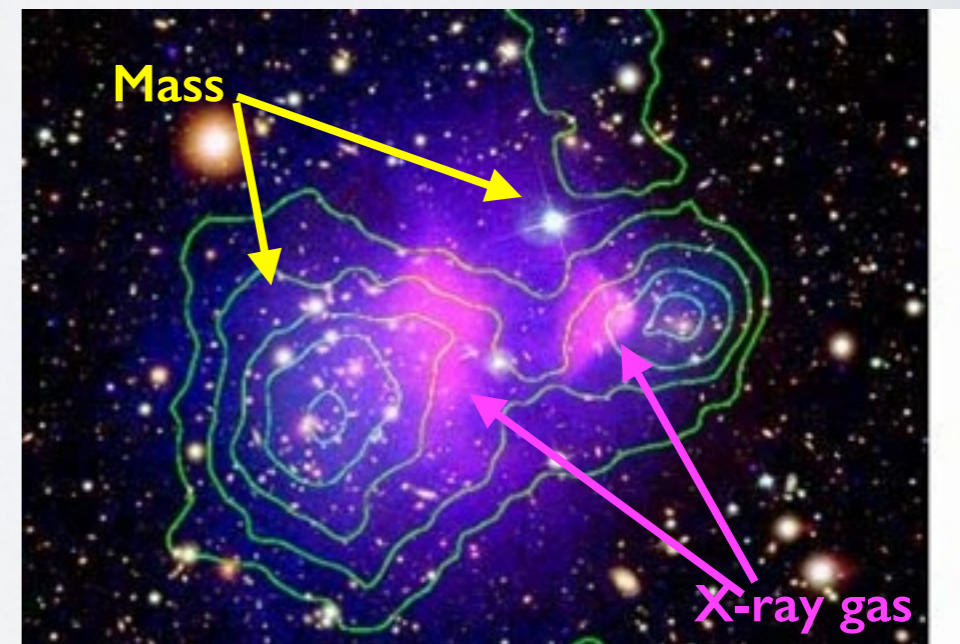
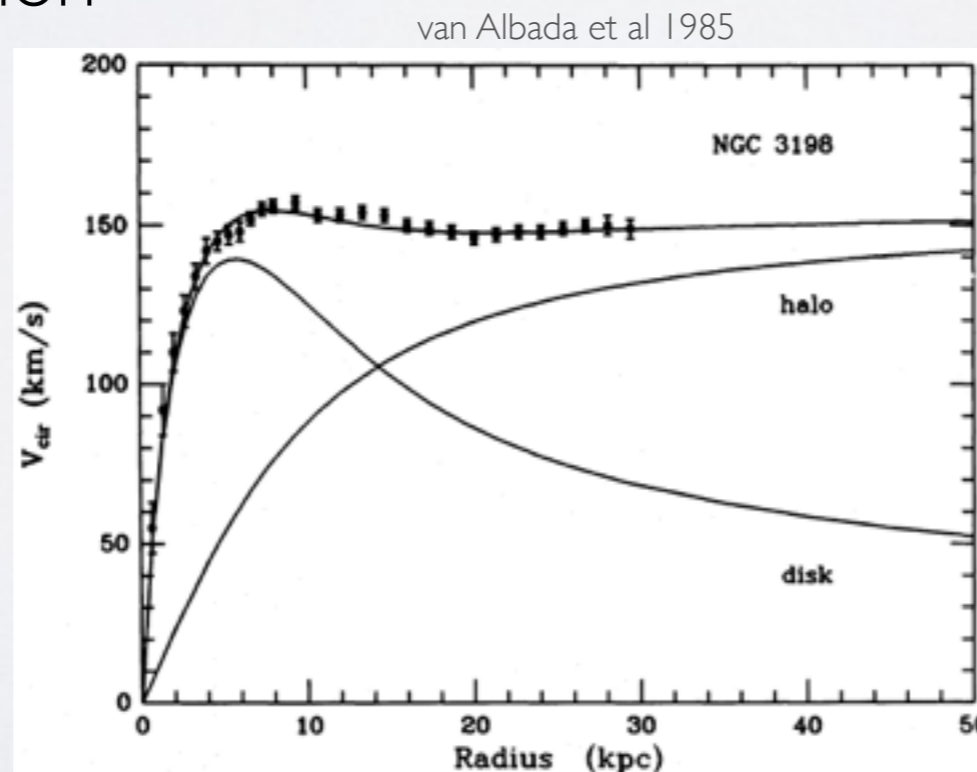
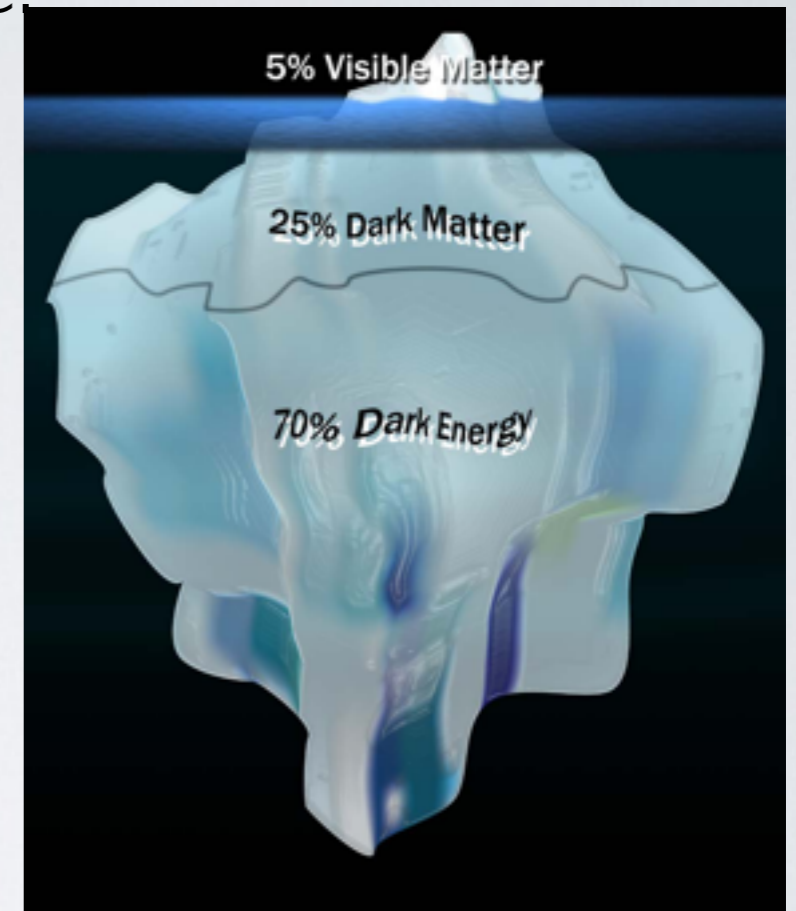


OUTLINE

- Introduction
- Motivation for Dark Matter Self Interactions
- Physics of Boosted Dark Matter
- Sources of BDM
- Detection of BDM
- Conclusions

DARK MATTER

- Dark Matter comprises about 25% of our Universe
- Astrophysical and Cosmological evidence:
 - ★ Galaxy rotation curves
 - ★ Gravitational Lensing
 - ★ Bullet cluster
 - ★ Dynamics of structure formation
 - ★ Velocity dispersion
 - ★ CMB Maps
 - ★ ...



Clowe et al

Four strategies for detection

- ★ Astrophysical Evidence
- ★ Indirect detection
- ★ Production at Colliders
- ★ Direct Detection

www.mpi-hd.mpg.de[available:10/31/14]

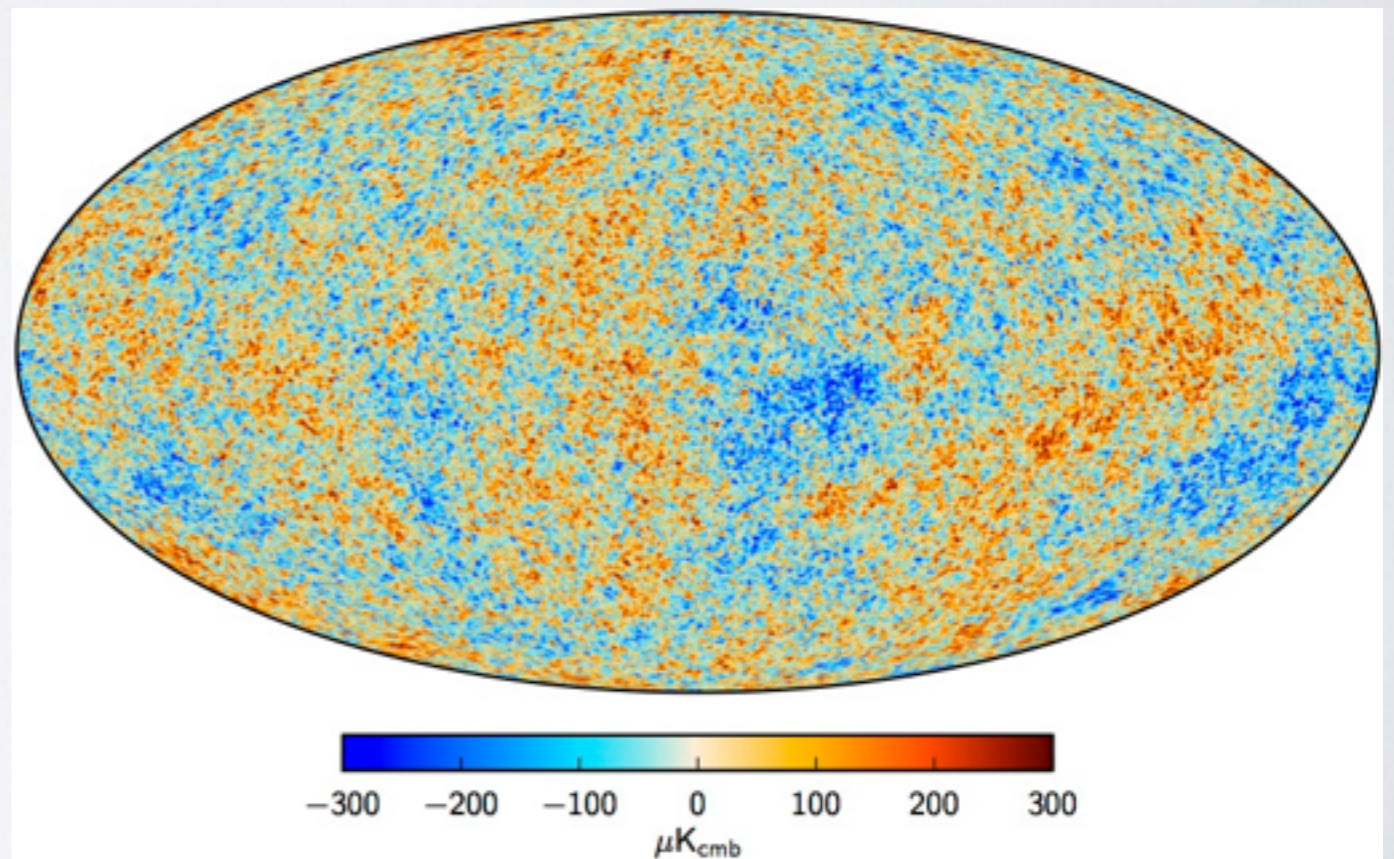
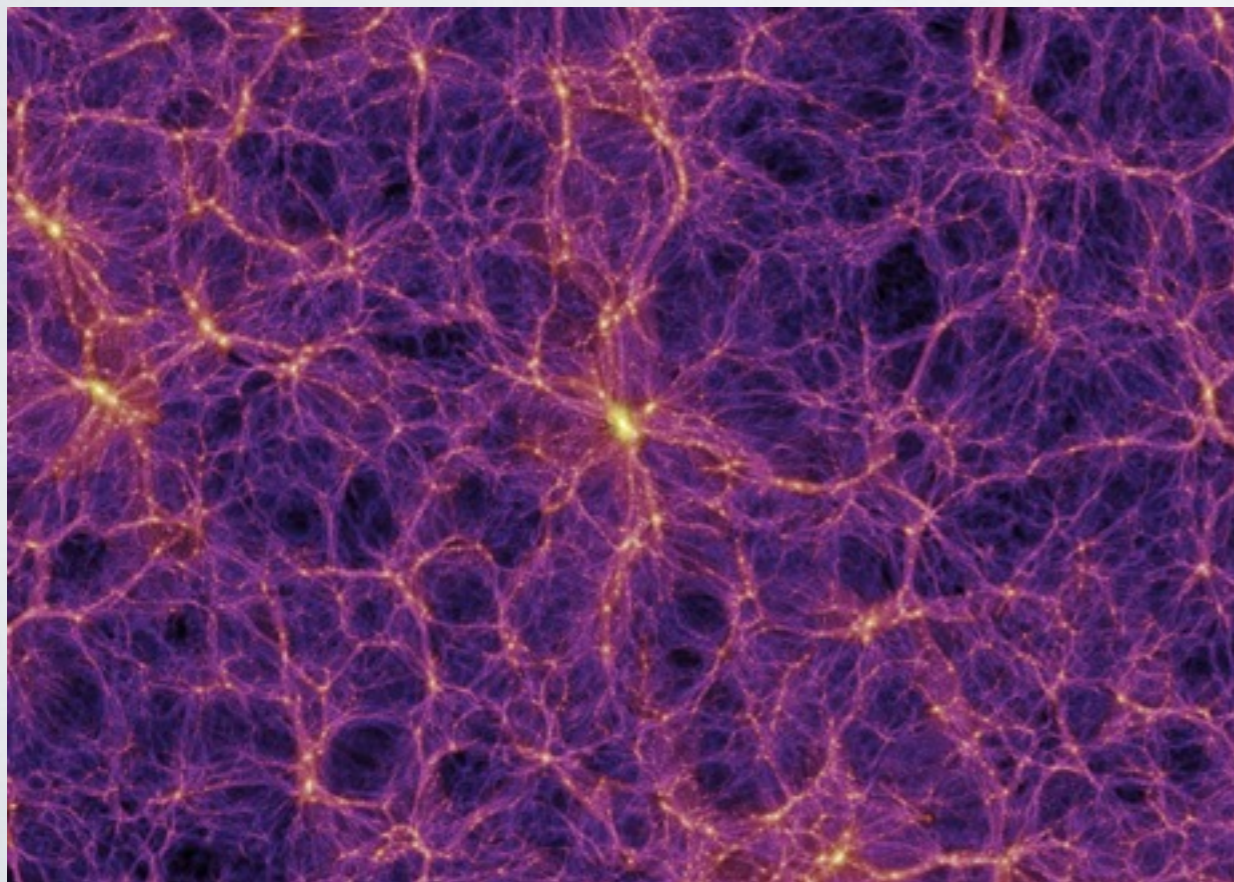
All complementary
and important



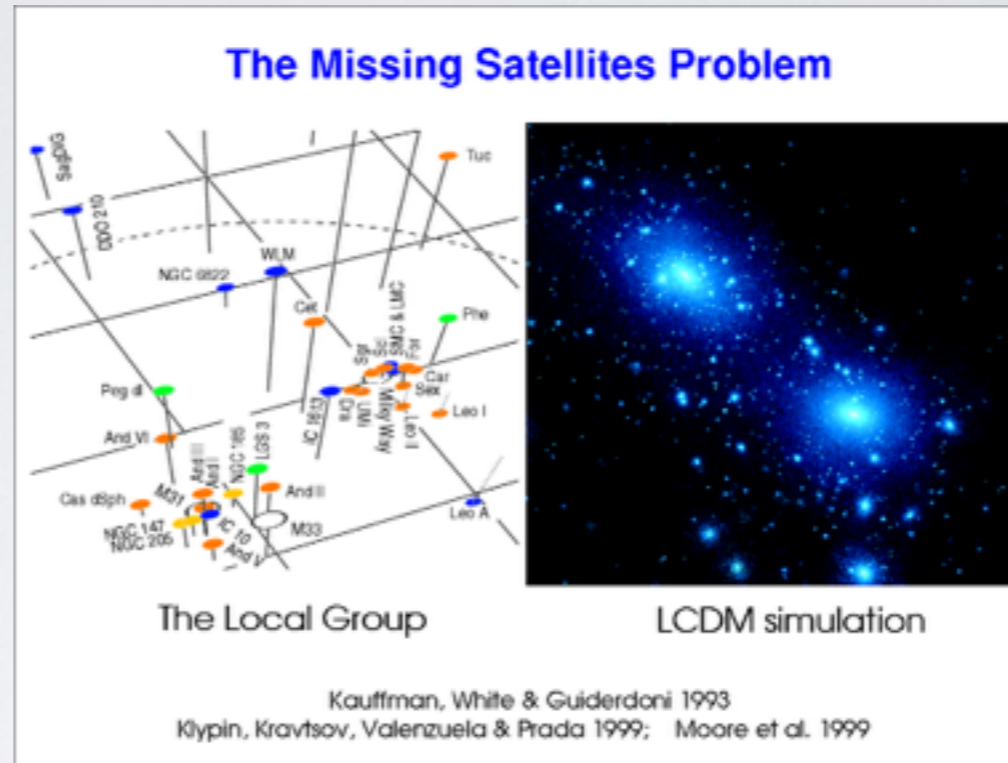
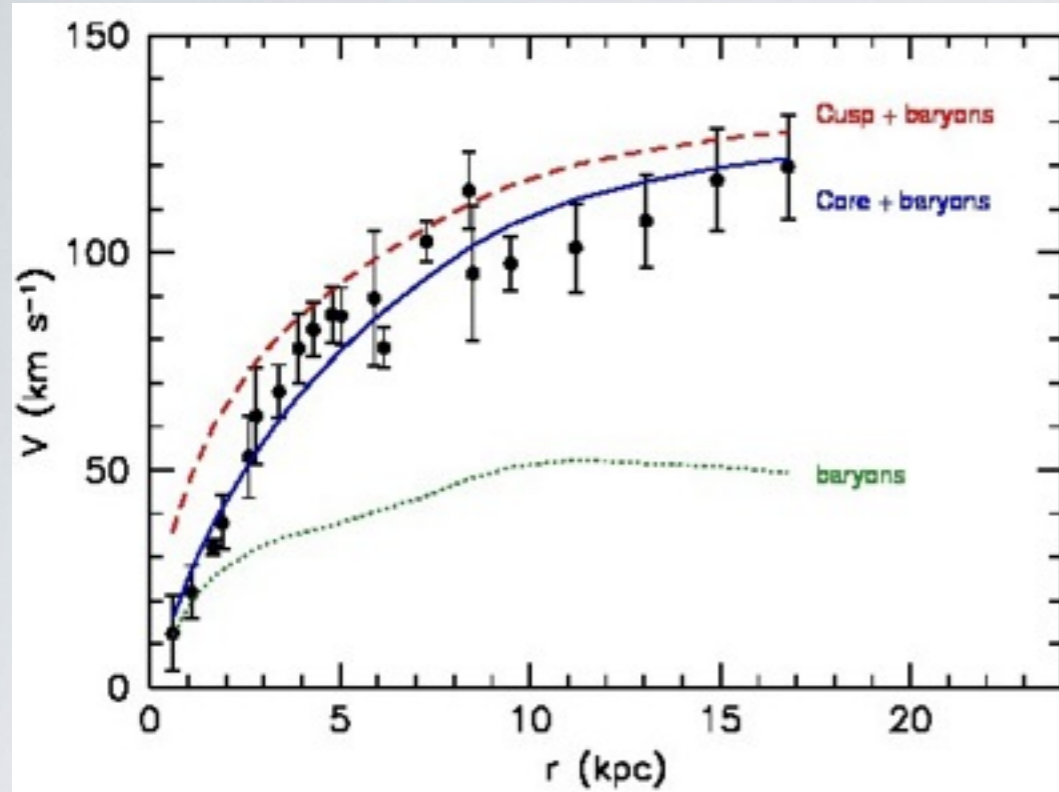
- Nature of DM is unknown
- Many Frameworks exist
- Compelling paradigm:

Collisionless Cold Dark Matter

- CDM simulations extremely successful at large scales



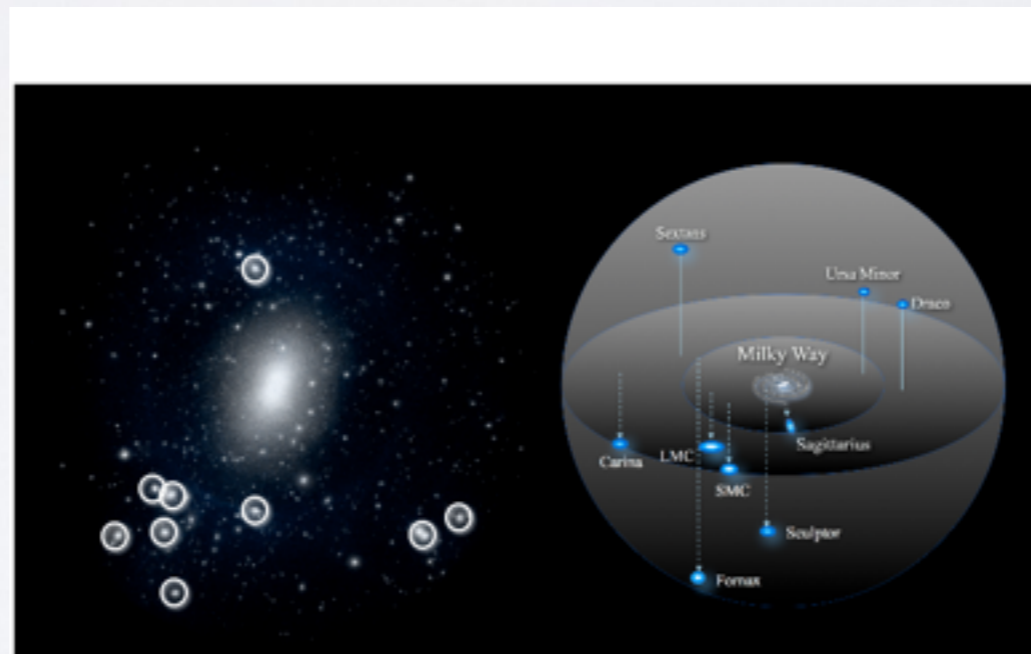
Potential Problems with CDM



Missing Satellites
CDM predicts more satellites than observed

Cusp-vs-cored

CDM predicts cusp density profile, but data fit by cored profile, Weinberg et al: arXiv 1306.0913



Too big to fail
CDM predicts more satellites than observed.

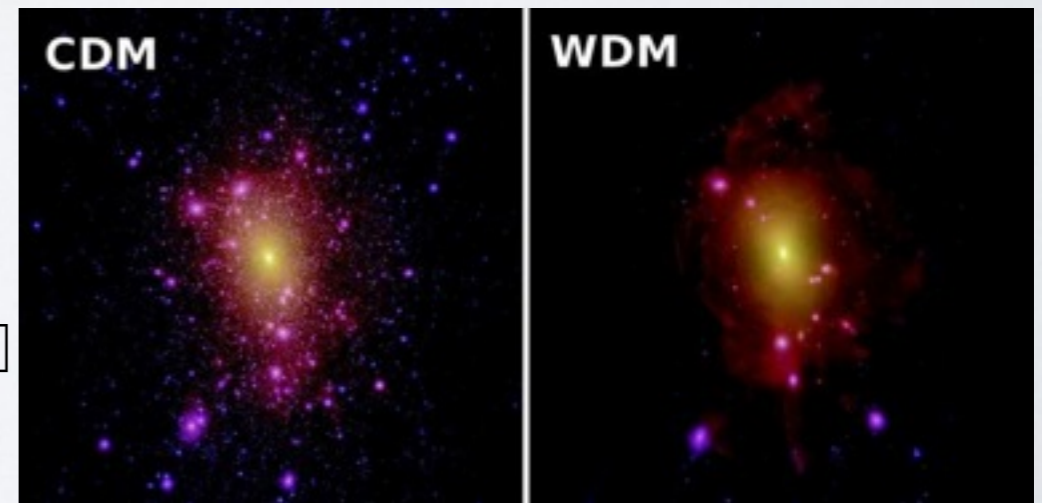
Weinberg et al: arXiv 1306.0913.

Boylan-Kolchin et al: arXiv MNRAS **415**, 2011

CDM predicts too Much Mass in Halos and Subhalos

Proposed Modifications to CDM

- Warm Dark Matter(WDM)
- Properties between HDM and CDM.
- WDM particles have masses $\sim \text{keV}$ and are ultra relativistic at decoupling. At later times become non-relativistic.
- Free-streaming scale is higher than that for CDM =>
- Primordial density fluctuations suppressed compared to CDM. =>
- Less smaller galaxies (Satellites) formed.
- Proposed candidate -> Sterile Neutrino
 - Sommer-Larsden & Dolgov (1999)[Astrophys.J. 551 (2001) 608-623]
 - Kamionkowski & Liddle (1999)[Phys.Rev.Lett. 84 (2000) 4525-4528]
 - Narayanan, Spergel et al(2000)[Astrophys.J. 543 (2000) L103-L106]



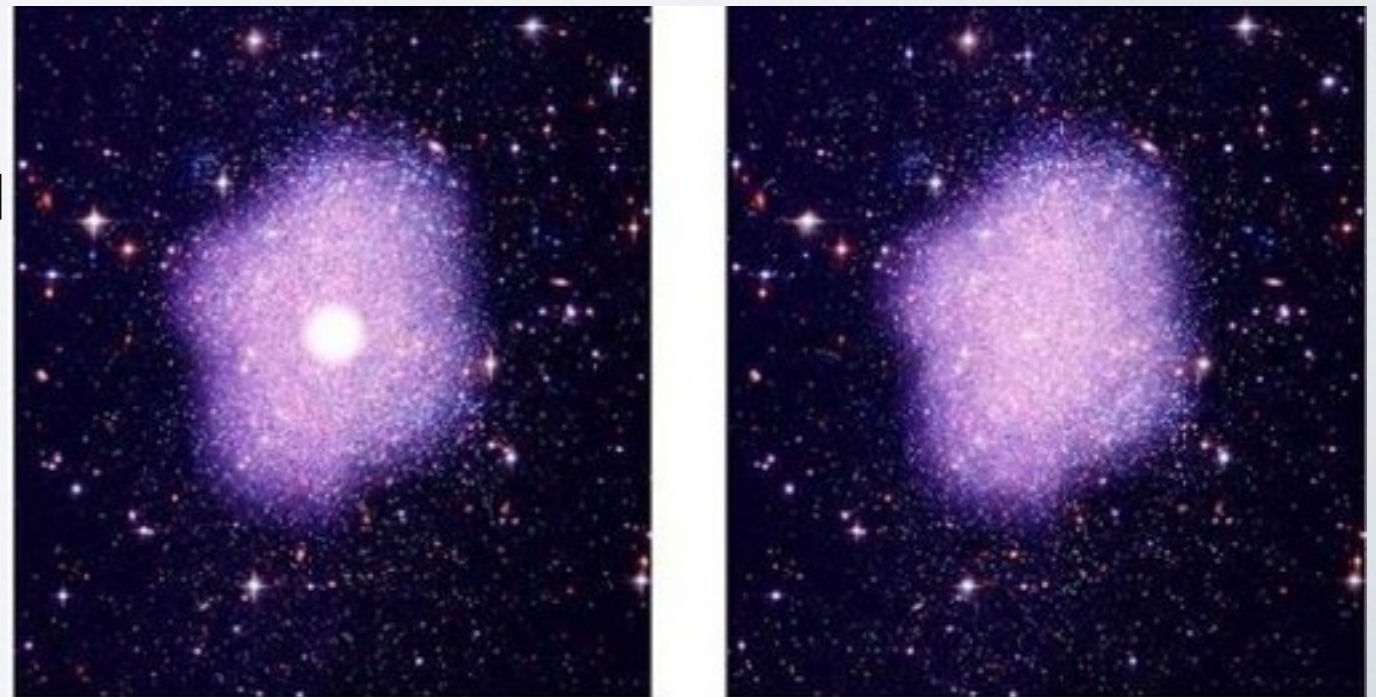
- Self Interacting Dark Matter(SIDM)
- DM particles with strong self-interactions.
- In early Universe, CDM and SIDM are same, collisions very small.
- After decoupling (self-scattering) collisions increase for SIDM => DM particles scatter out from center of Halo.
 - Spergel & Steinhard(2000)[Phys.Rev.Lett. 84 (2000) 3760-3763]
 - Ostriker et al (2000)[Phys.Rev.Lett. 84 (2000) 5258-5260]
 - Dave et al (2000)[Astrophys.J. 547 (2001) 574-589]
 - Buckley & Fox (2010) [Phys.Rev. D81 (2010) 083522]

Kavli IPMU, Available[08/24/15]

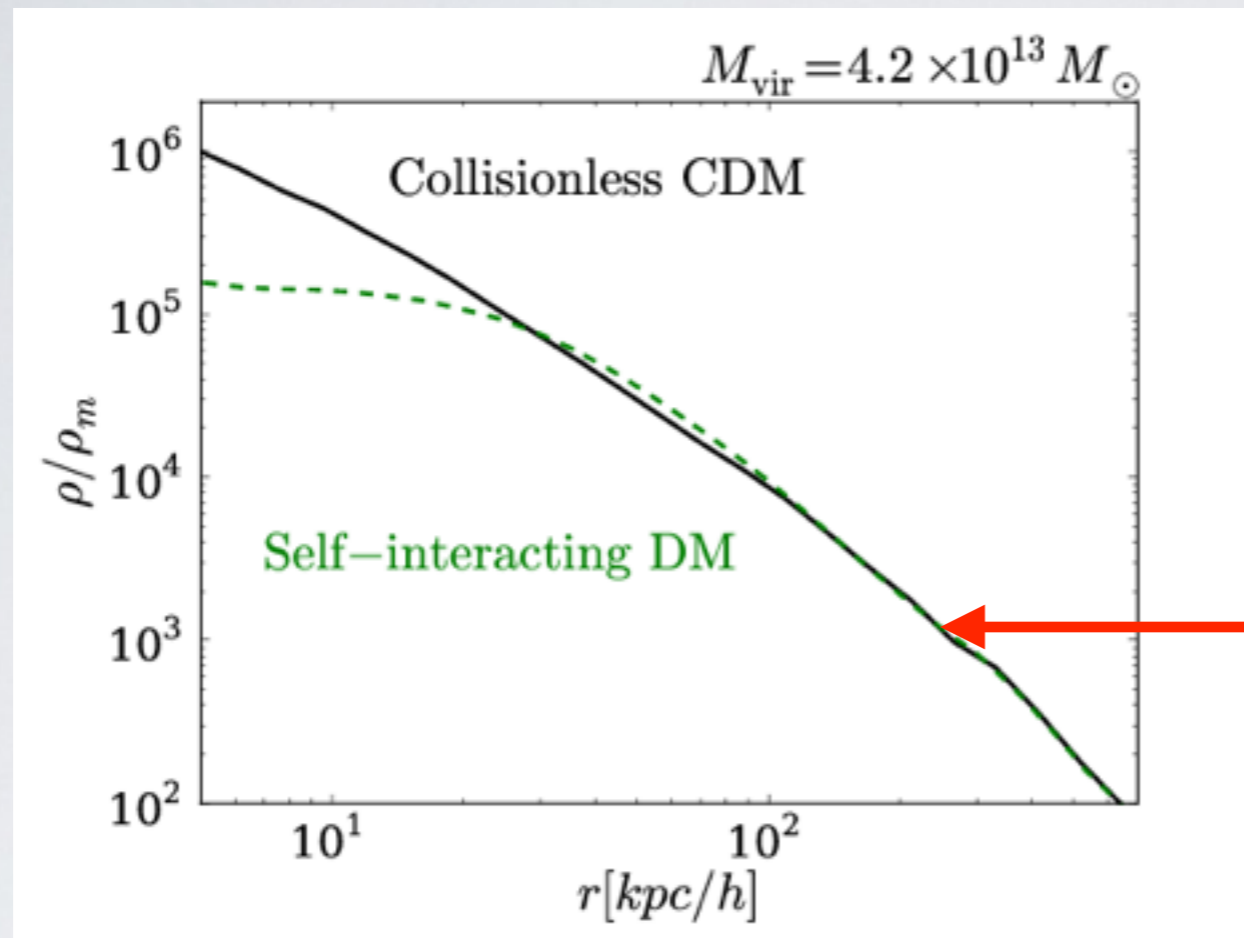
- Self Interacting WDM(SIWDM)

- Hannestad & Scherrer(2000)[Phys. Rev. D, 62, 042522]

Based on work by Hochberg,
Murayama et al (2014)



Self-Interacting Dark Matter (SIDM) Cont'd.



Weinberg et al:
arXiv 1306.0913

Solves some
discrepancies in CDM:
cusp-vs-cored

- Spergel and Steinhardt (2000): $0.5 \text{ cm}^2/\text{g} < \sigma_{\chi\chi}/M_{\chi} < 6 \text{ cm}^2/\text{g}$
 $8.9 \times 10^{11} \text{ pb/GeV} < \sigma_{\chi\chi}/M_{\chi} < 1.1 \times 10^{13} \text{ pb/GeV}$
- Wandelt et al (2000): $0.1 \text{ cm}^2/\text{g} < \sigma_{\chi\chi}/M_{\chi} < 6 \text{ cm}^2/\text{g}$
- Matter distribution of Bullet Cluster (Randall et al, 2008) & kinematics of dwarf spheroidal galaxies (Zavala et al, 2013) place limits on $\sigma_{\chi\chi}/M_{\chi}$



SIDM effective if $0.1 \text{ cm}^2/\text{g} < \sigma_{\chi\chi}/M_{\chi} < 1.25 \text{ cm}^2/\text{g}$

i.e. $1.79 \times 10^{11} \text{ pb/GeV} < \sigma_{\chi\chi}/M_{\chi} < 2.22 \times 10^{12} \text{ pb/GeV}$

- Very recently (April 2015), evidence for DM self-interactions from Abell 3827 (R Massey et al. 2015 & Karlhofer et al. 2015).
- Observed lagging halo after merger of 4 galaxies in the Cluster.
- Gravitational Lensing were able to constrain self interactions strength.

$$\sigma_{\chi\chi}/M_{\chi} \sim 1.5 \text{ cm}^2/\text{g}$$

Nature of DM => UNKNOWN

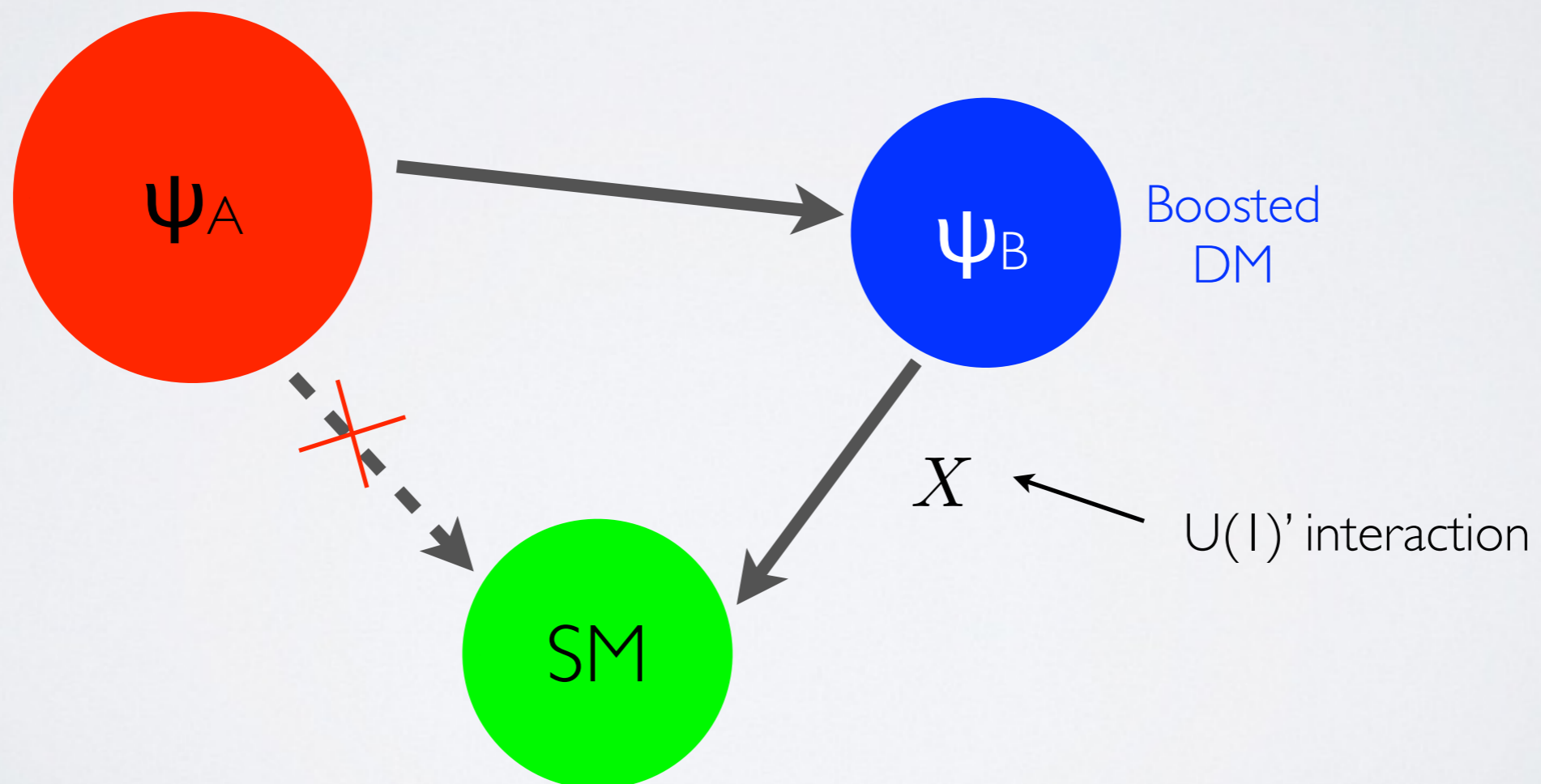
- Single component?
 - Kamionkowski et al (1987), Bergstrom. L (2000), Bertone et al (2005). (Review)
 - Many different scenarios of DM.
- Multi-component?
 - Agashe et al. [JCAP 1410 (2014) 10]
 - Berger et al. [JCAP 1502 (2015) 02, 005]

Self Interacting ?

- Single component?
 - Zentner et al. [Phys.Rev. D80 (2009) 063501]
 - Alberquerque et al. [JCAP 1402 (2014) 047]
 - Chen et al. [JCAP 1410 (2014) 10, 049]
- Multi-component DM with Self-interactions
 - Kong, **GM** & Park (2014)

BASIC SETUP

- Two species of DM: ψ_A and ψ_B with $M_A > M_B$. (eg. $U(1)' \otimes U(1)''$)
- ψ_A is dominant and has no direct coupling to SM
- ψ_B is sub-dominant, direct coupling to SM



BASIC FEATURES

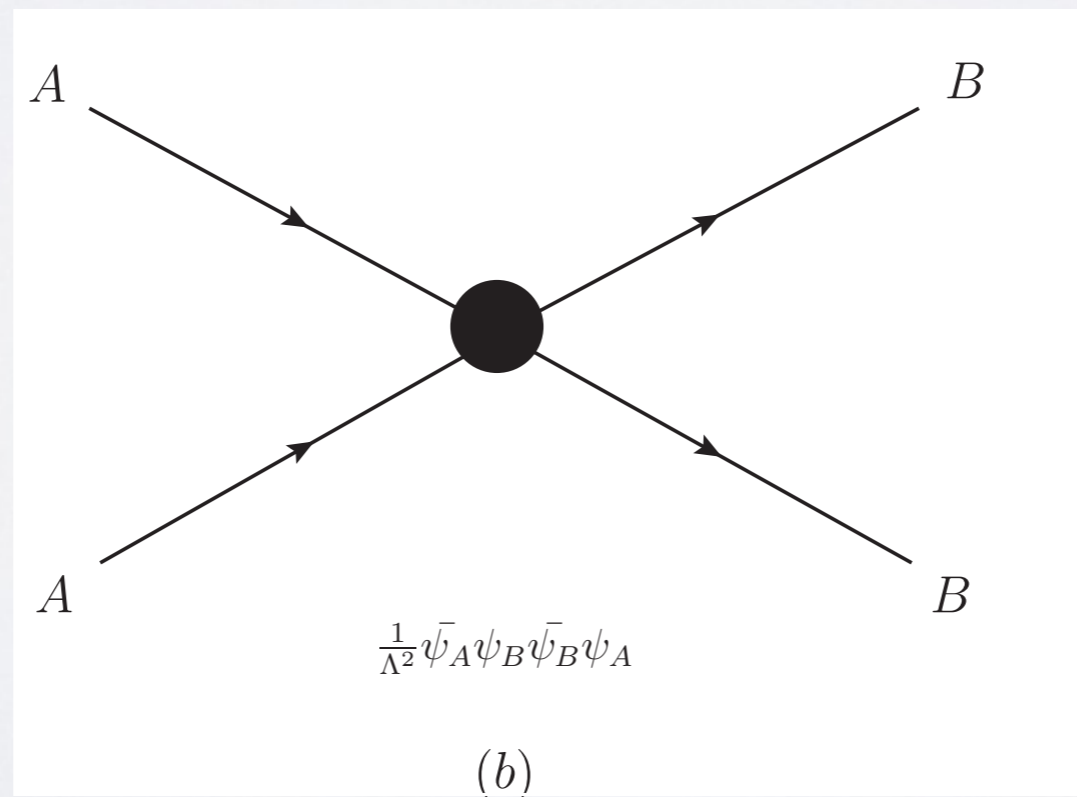
- Relic density of ψ_A is set by annihilation into ψ_B

$$\psi_A \bar{\psi}_A \rightarrow \psi_B \bar{\psi}_B \quad \text{Assisted Freeze-out Mechanism:}$$

Belanger & Park
JCAP 1203(2012)038

- Annihilation products, ψ_B are boosted with factor $\gamma = M_A/M_B$
- ‘Boosted Dark Matter’
- Indirect detection of ψ_A through boosted ψ_B

$$\frac{1}{\Lambda^2} \bar{\psi}_A \psi_A \bar{\psi}_B \psi_B$$



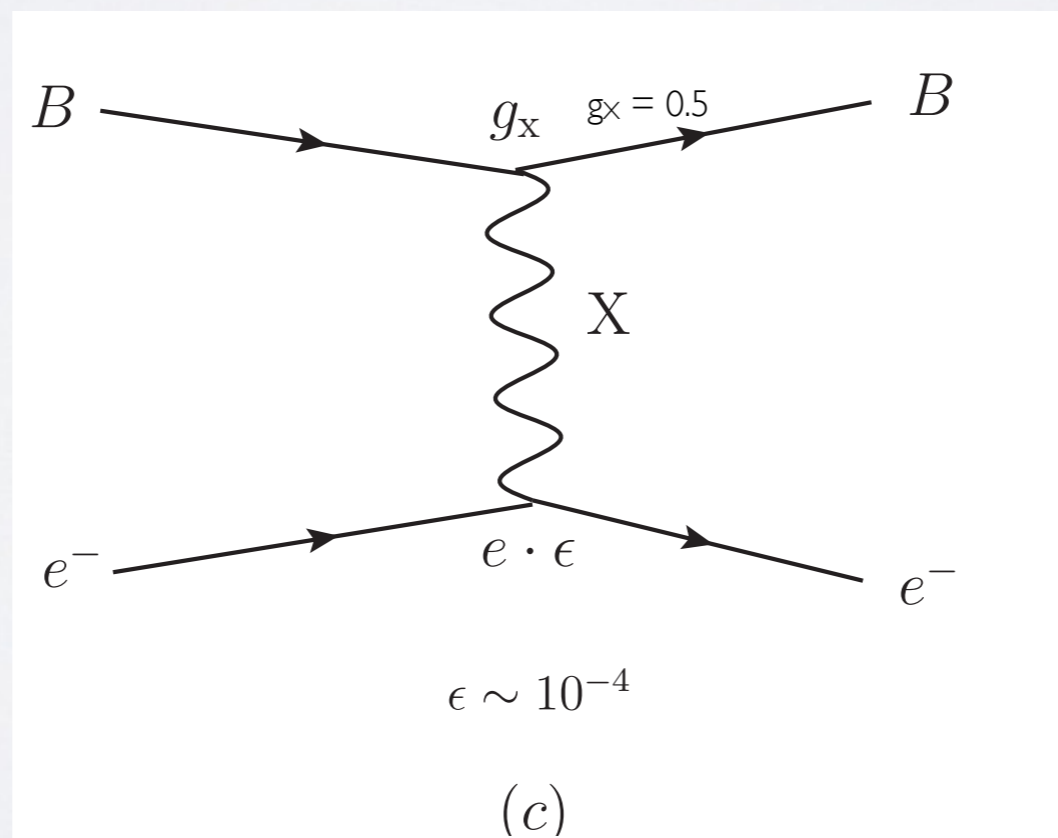
Agashe et al (arXiv: 1405.7370)

- Detect boosted ψ_B through its interaction with SM

$$\mathcal{L} \supset -\frac{1}{2} \sin \epsilon X_{\mu\nu} F^{\mu\nu} \quad \text{Interaction of photon with hidden Boson}$$

- Via kinetic mixing of SM photon with hidden 'Dark' X
- Direct detection of boosted ψ_B through SM
- Indirect-direct detection of ψ_A

Smoking Gun
for Non-Minimal
DM sector.



BDM FROM GALACTIC CENTER

- Agashe et al. [JCAP 1410 (2014) 10] examine flux of BDM in GC from annihilation of ψ_A
- Calculate Flux using NFW density profile

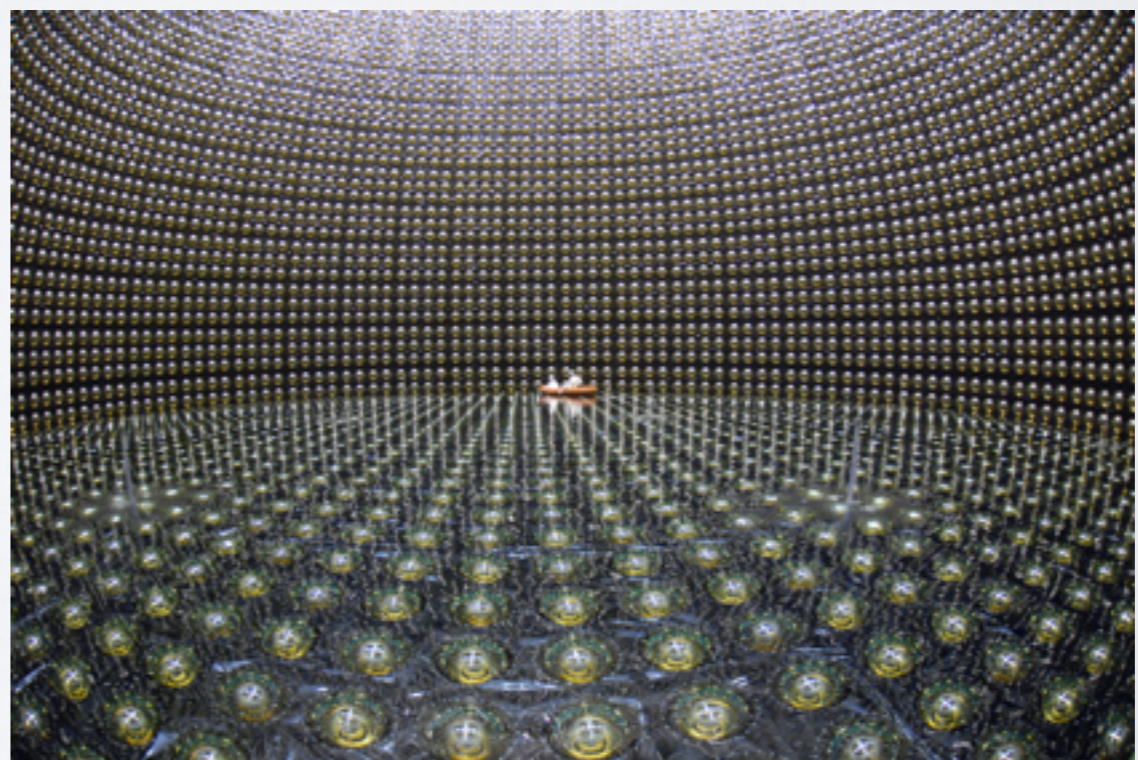
$$\Phi_{GC}^{10^\circ} = 9.9 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \left(\frac{\langle \sigma_{A\bar{A} \rightarrow B\bar{B} \nu} \rangle}{5 \times 10^{-26} \text{ cm}^3/\text{s}} \right) \left(\frac{20 \text{ GeV}}{m_A} \right)^2$$

- Low Flux means need large volume detectors sensitive to

$$\psi_B + SM \rightarrow \psi_B + SM$$

- Neutrino detectors: Super-K,
Hyper-K, Ice-Cube, PINGU

What about Point Sources?



BOOSTED DM FROM THE SUN

- Time evolution of number density of DM particles in sun is:

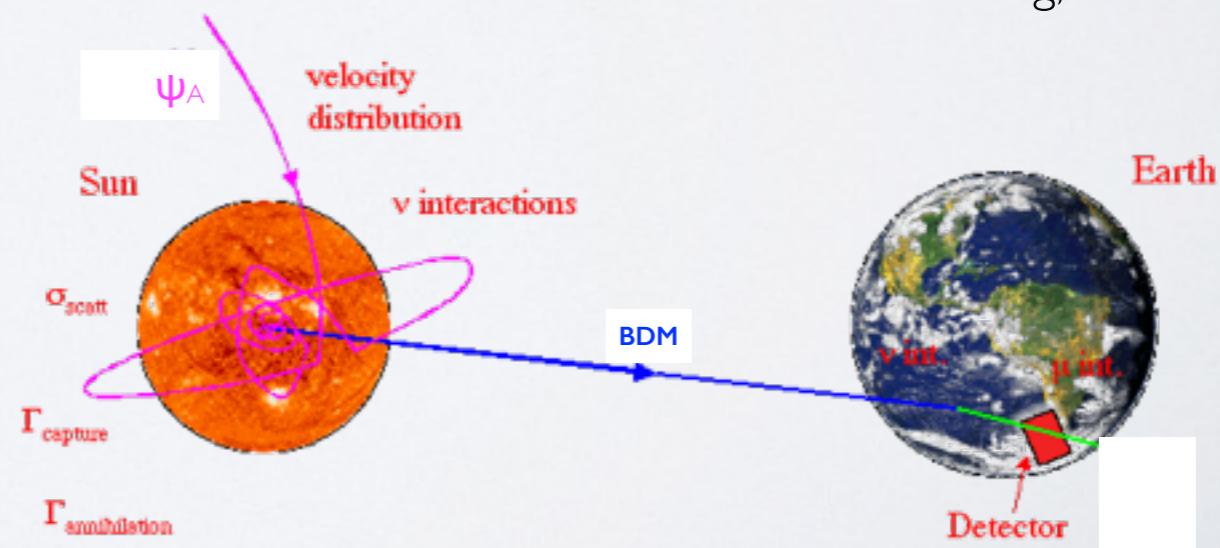
$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2 \quad \text{Chen, Lee, Lin \& Lin(2014)}$$

- ♦ **C_c**: capture rate by nuclei inside Sun
- ♦ **C_s**: capture rate by DM already captured in Sun
- ♦ **C_e**: Evaporation rate due to DM-nuclei scattering
- ♦ **C_{se}**: evaporation rate due to DM-self interaction
- ♦ **C_a**: annihilation rate

Kong, **GM** & Park, 2014.

- Sun is point source

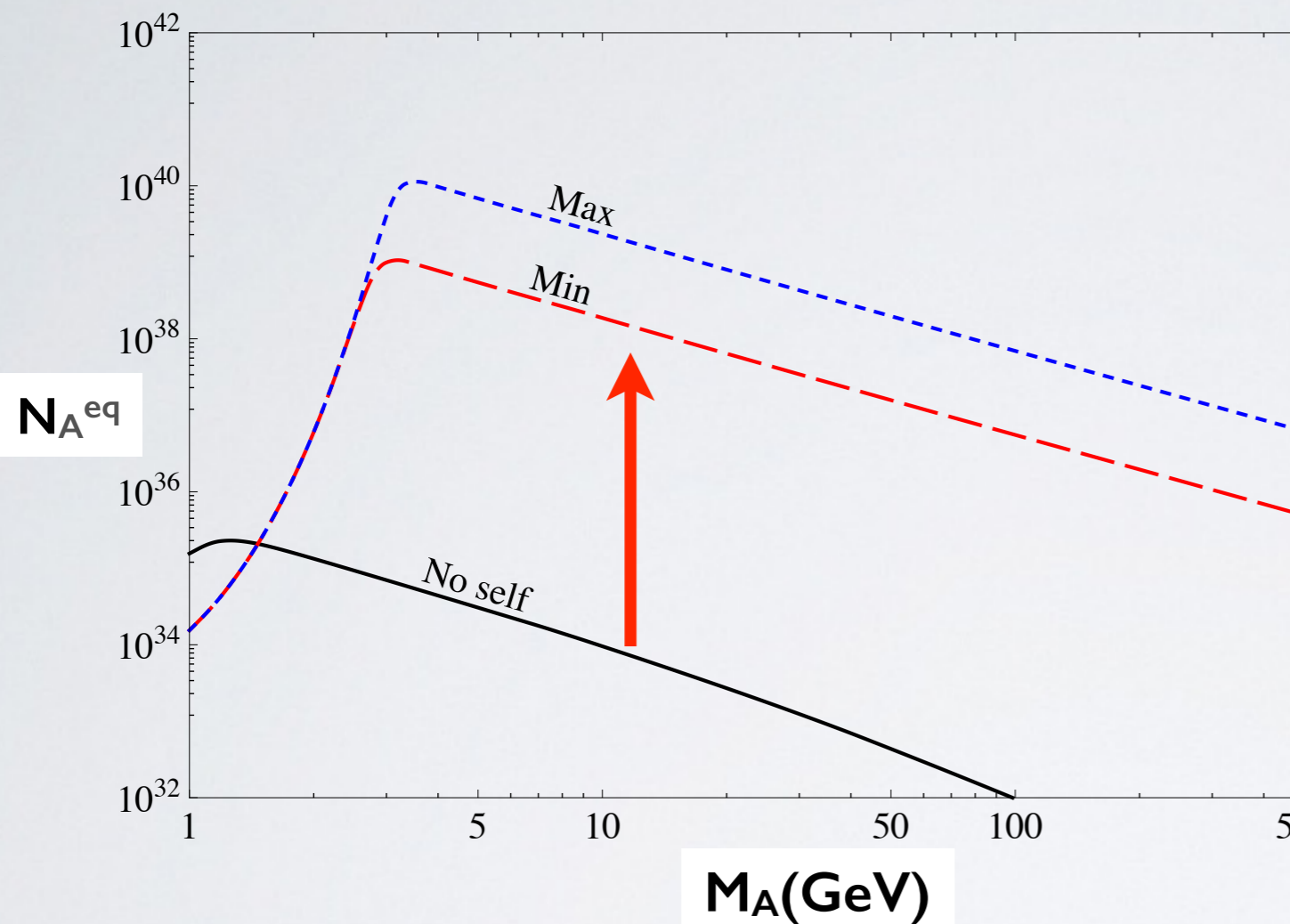
Berger et al (arXiv:1410.2246)



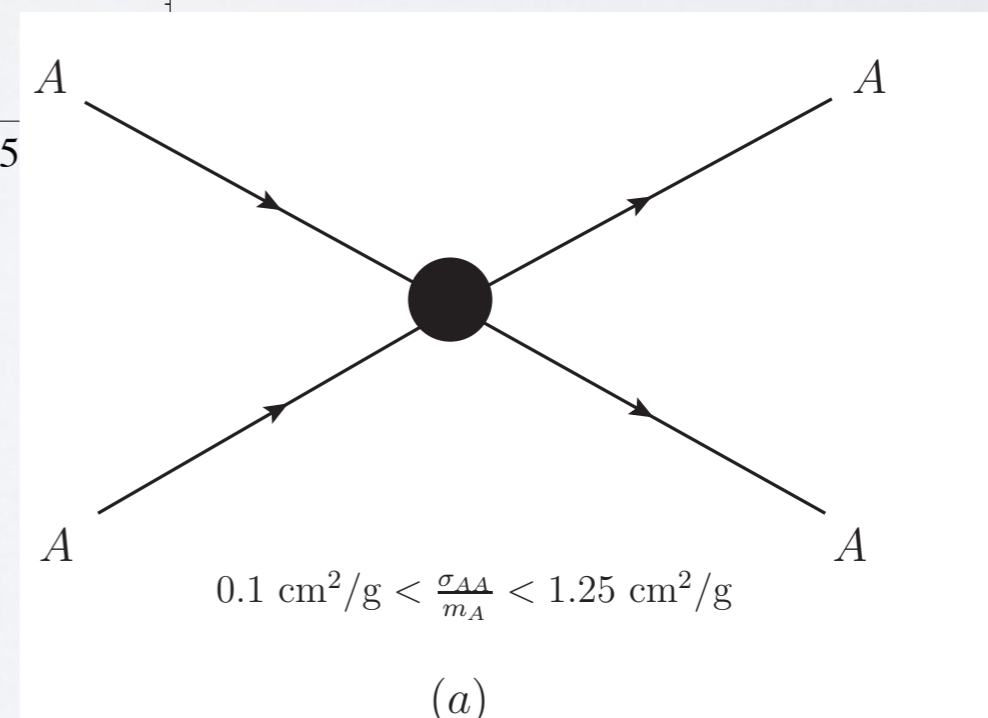
$$N_{\chi}(t) = \frac{C_c \tanh(t/\tau_{\text{eq}})}{\tau_{\text{eq}}^{-1} - (C_s - C_e) \tanh(t/\tau_{\text{eq}})/2}$$

$$\tau_{\text{eq}} = \frac{1}{\sqrt{C_c(C_a + C_{se}) + (C_s - C_e)^2/4}},$$

$$N_A^{\text{eq}}: m_B=0.2 \text{ GeV}, m_X=20 \text{ MeV}, \epsilon=10^{-4}, g_X=0.5$$




Importance of Self-Interaction



Flux of boosted DM particles

- Flux of boosted ψ_B from the Sun:

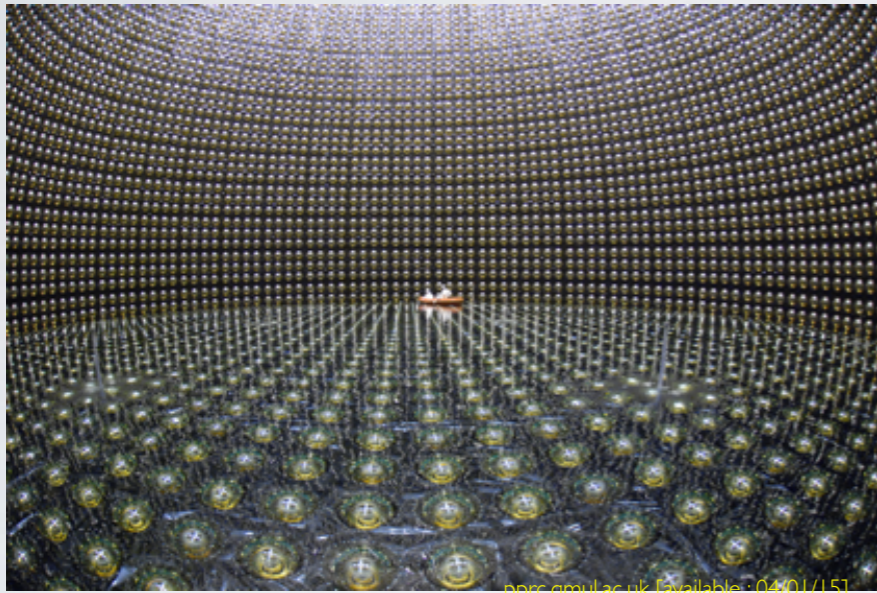
$$\frac{d\Phi_B^{\text{Sun}}}{dE_B} = \frac{\Gamma_A^{\psi_A}}{4\pi R_{\text{Sun}}^2} \frac{dN_B}{dE_B} \quad \Gamma_A^{\psi_A} = \frac{C_a}{2} N_{\psi_A}^2$$

$$\frac{dN_B}{dE_B} = 2\delta(E_B - m_A)$$


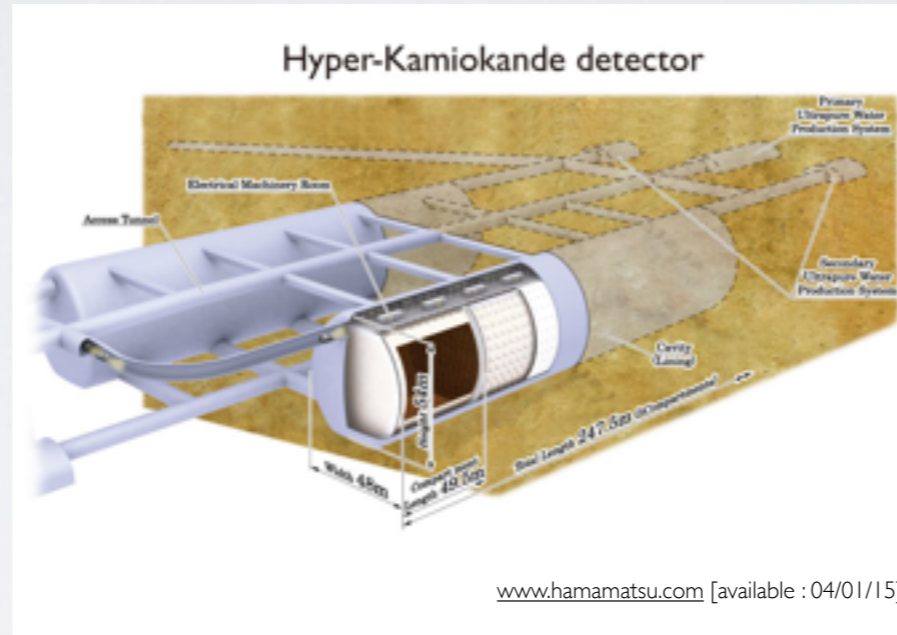
- Annihilation of ψ_A produces 2 mono-energetic boosted ψ_B 's
- Take into account other factors, e.g. energy loss of the ψ_B particles during propagation through the sun

DETECTION OF BDM

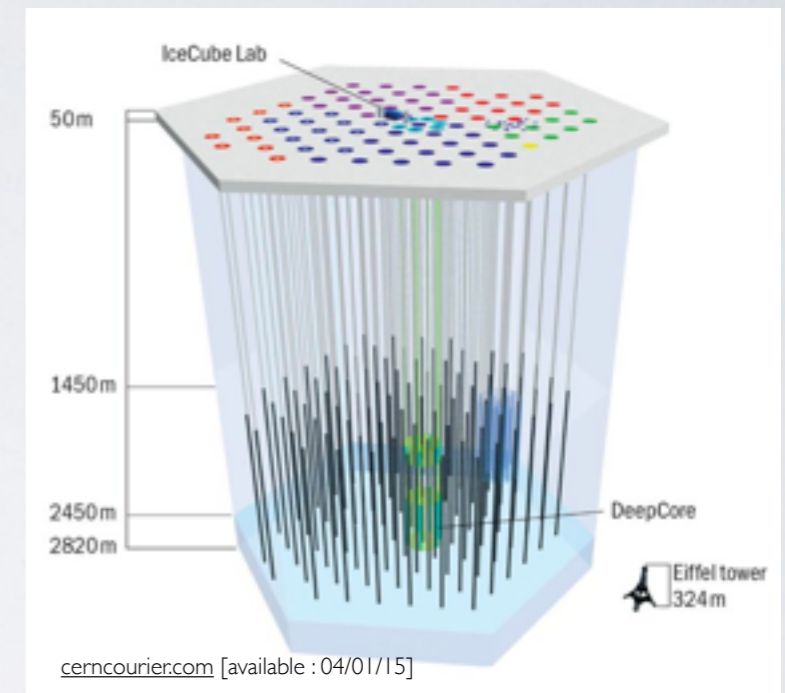
- large volume neutrino detectors detect: $\nu_e n \rightarrow e^- p$



Super-K



Hyper-K



PINGU/Ice-Cube

- In same light BDM detected through $\psi_B e^- \rightarrow \psi_B e^-$
- Energetic electrons would produce Cherenkov light
- BDM signal seen as single Cherenkov ring

- Focus on Super-K, Hyper-K and PINGU.

Experiment	Volume (MTon)	Ethres(GeV)	res(deg)
Super-K	0.0224	0.01	3
Hyper-K	0.56	0.01	3
PINGU	0.5	1	23
Ice-Cube	1000	100	30

- Angular resolution and energy threshold **important** for distinguishing Neutrino backgrounds

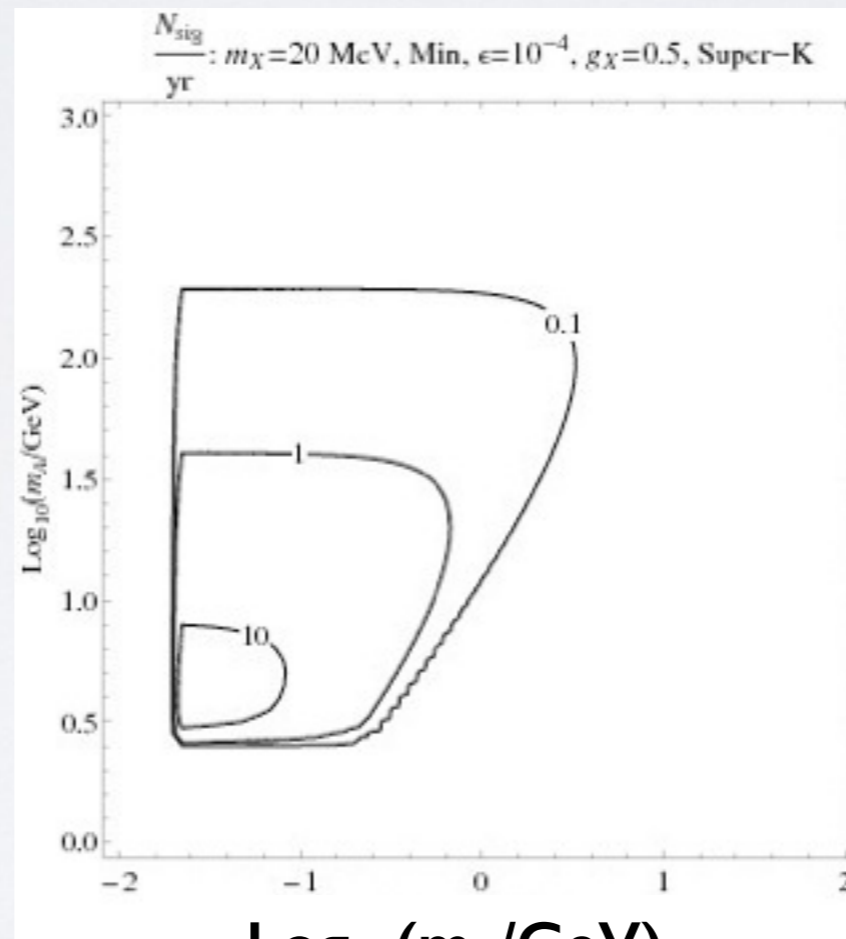
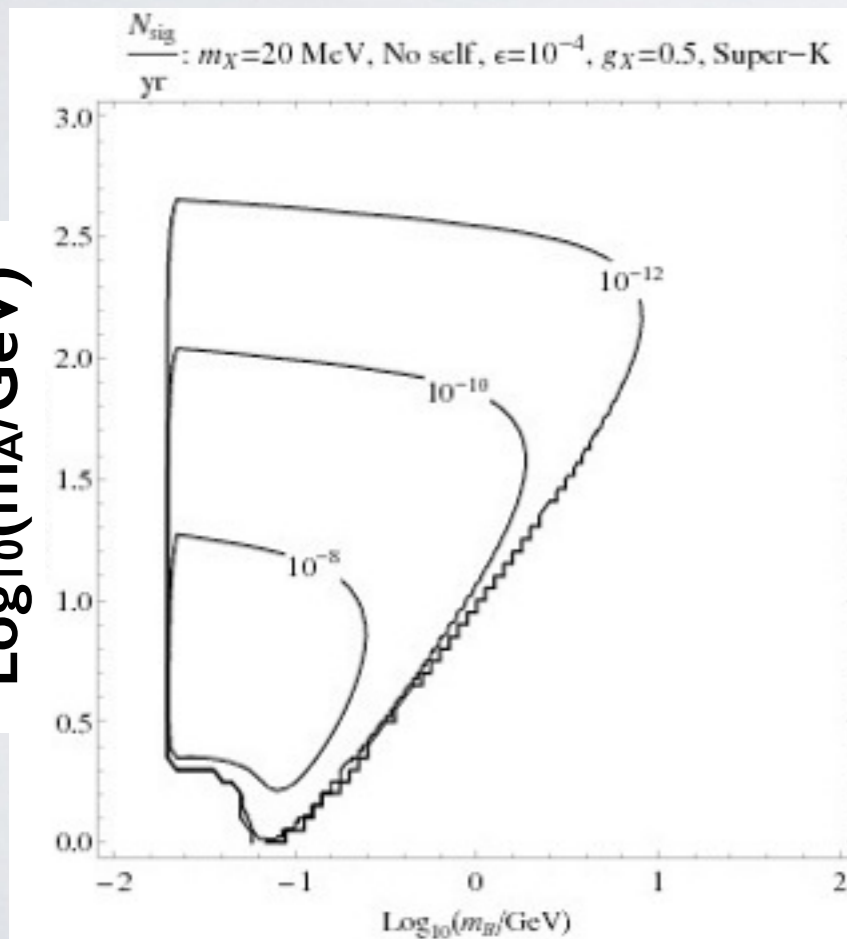
Signal Rates

$$N_{\text{sig}} = \Delta T \frac{10 \rho_{\text{target}} V_{\text{exp}}}{m_{\text{H}_2\text{O}}} \frac{2\Gamma_A^{\psi A}}{4\pi R_{\text{Sun}}^2} \int_{E_e^{\text{min}}}^{E_e^{\text{max}}} dE_e \frac{d\sigma_{Be^- \rightarrow Be^-}}{dE_e}$$

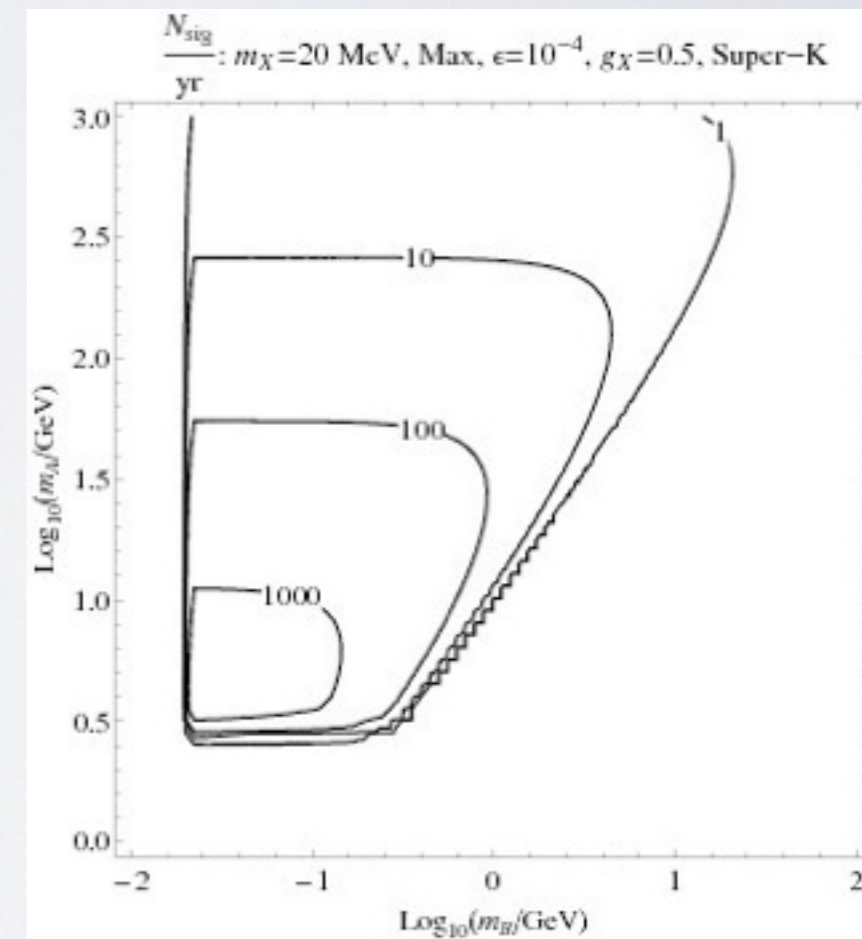
- For Super-K.

Kong, **GM** & Park, 2014.

$\text{Log}_{10}(m_A/\text{GeV})$



$\text{Log}_{10}(m_B/\text{GeV})$



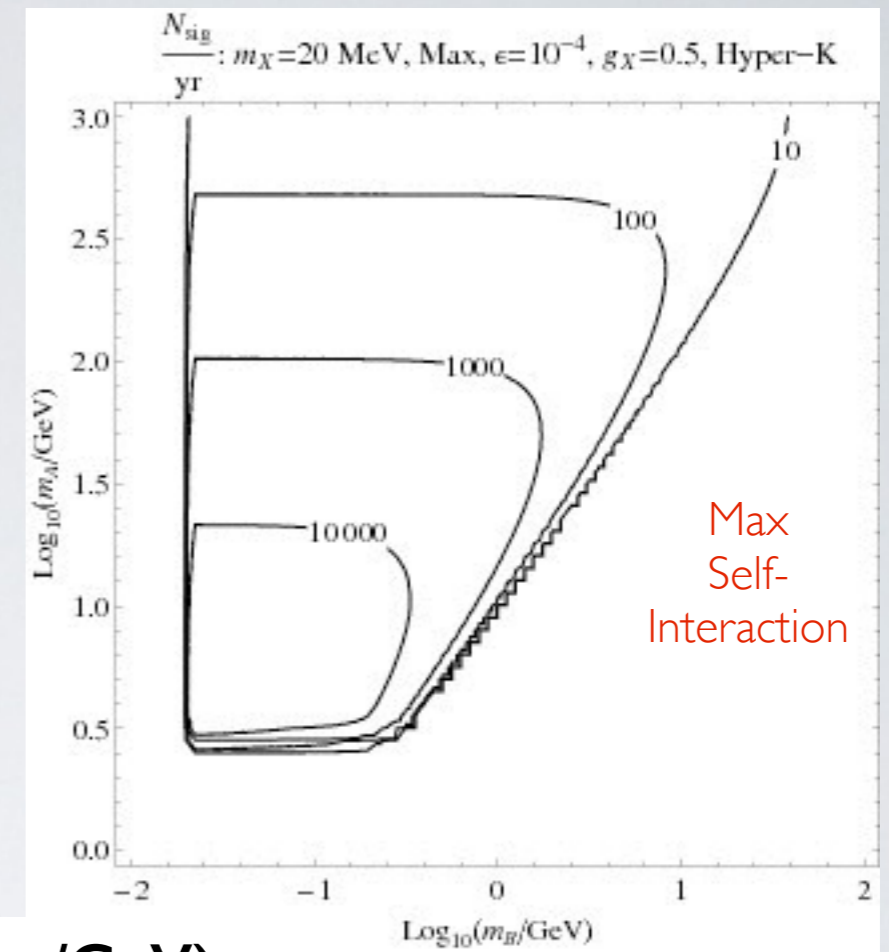
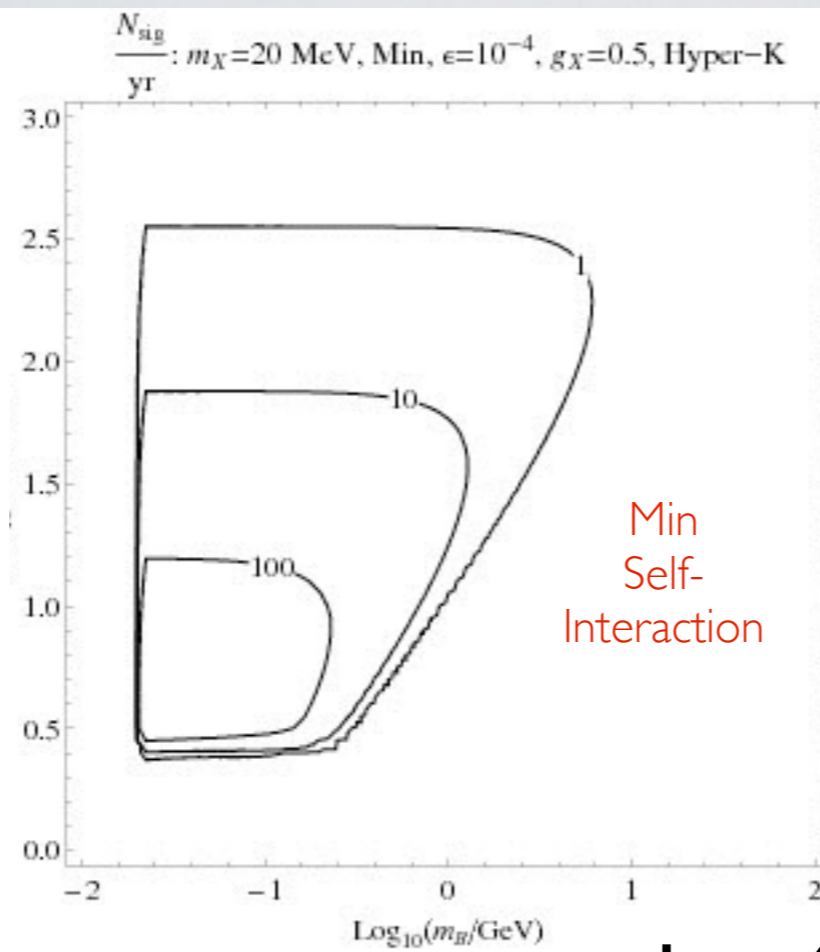
No self-interaction

Min self-interaction

Max self-interaction

- For Hyper-K

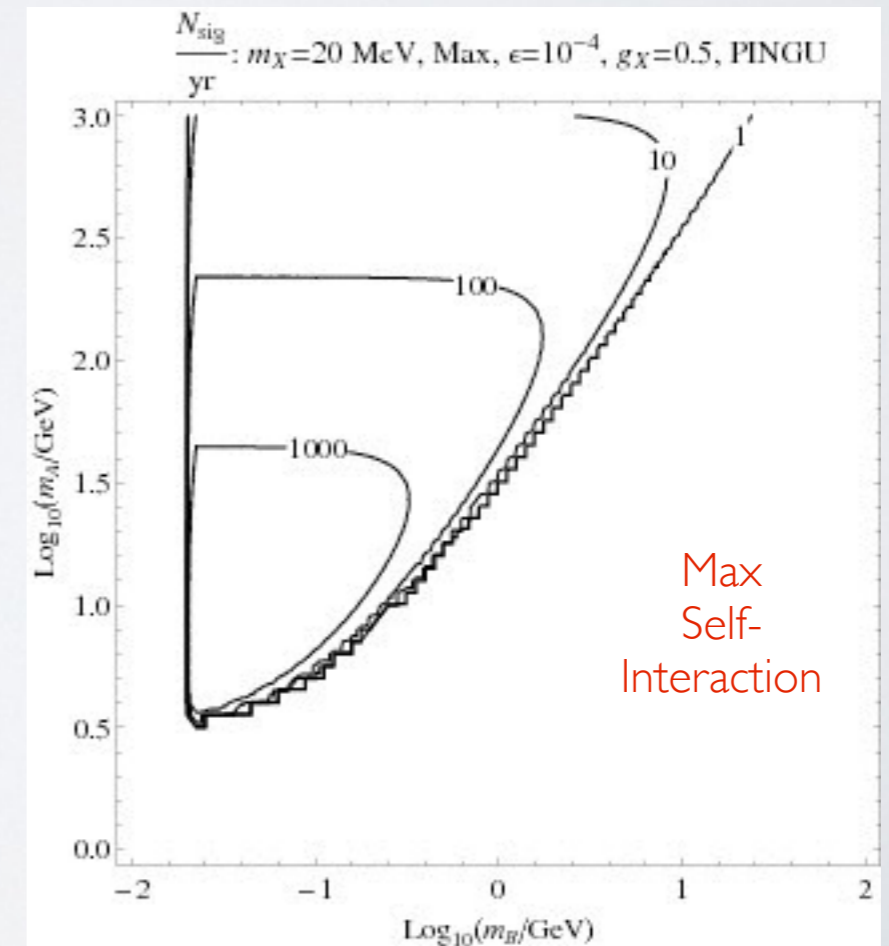
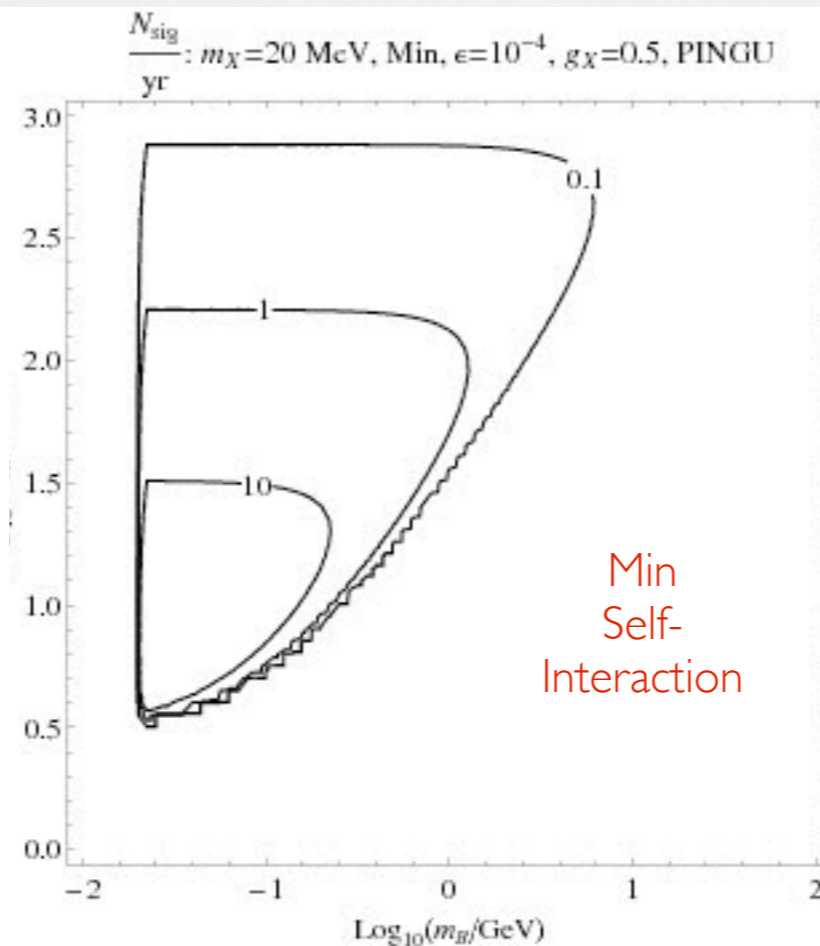
$\text{Log}_{10}(m_A/\text{GeV})$



$\text{Log}_{10}(m_B/\text{GeV})$

- For PINGU

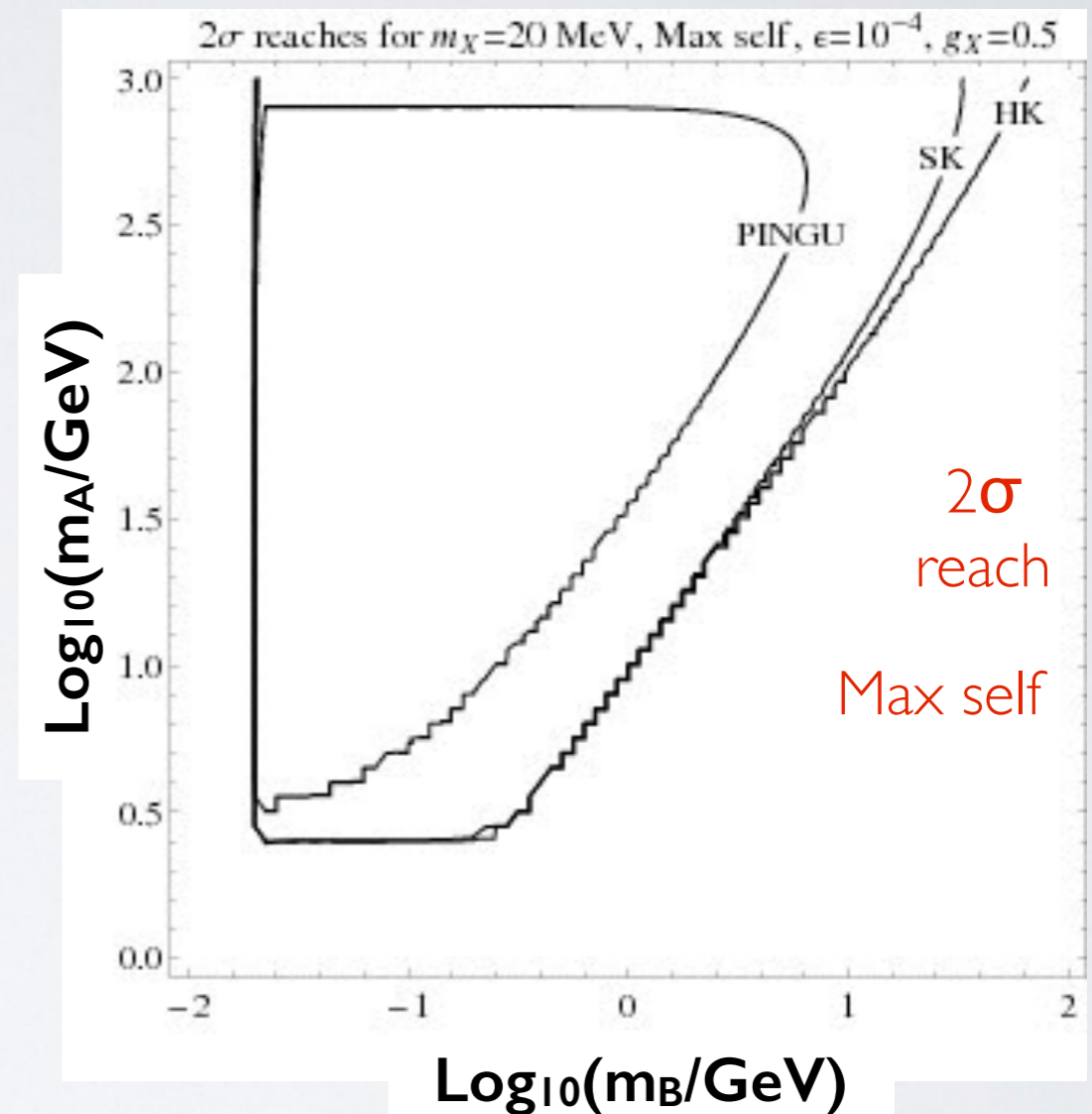
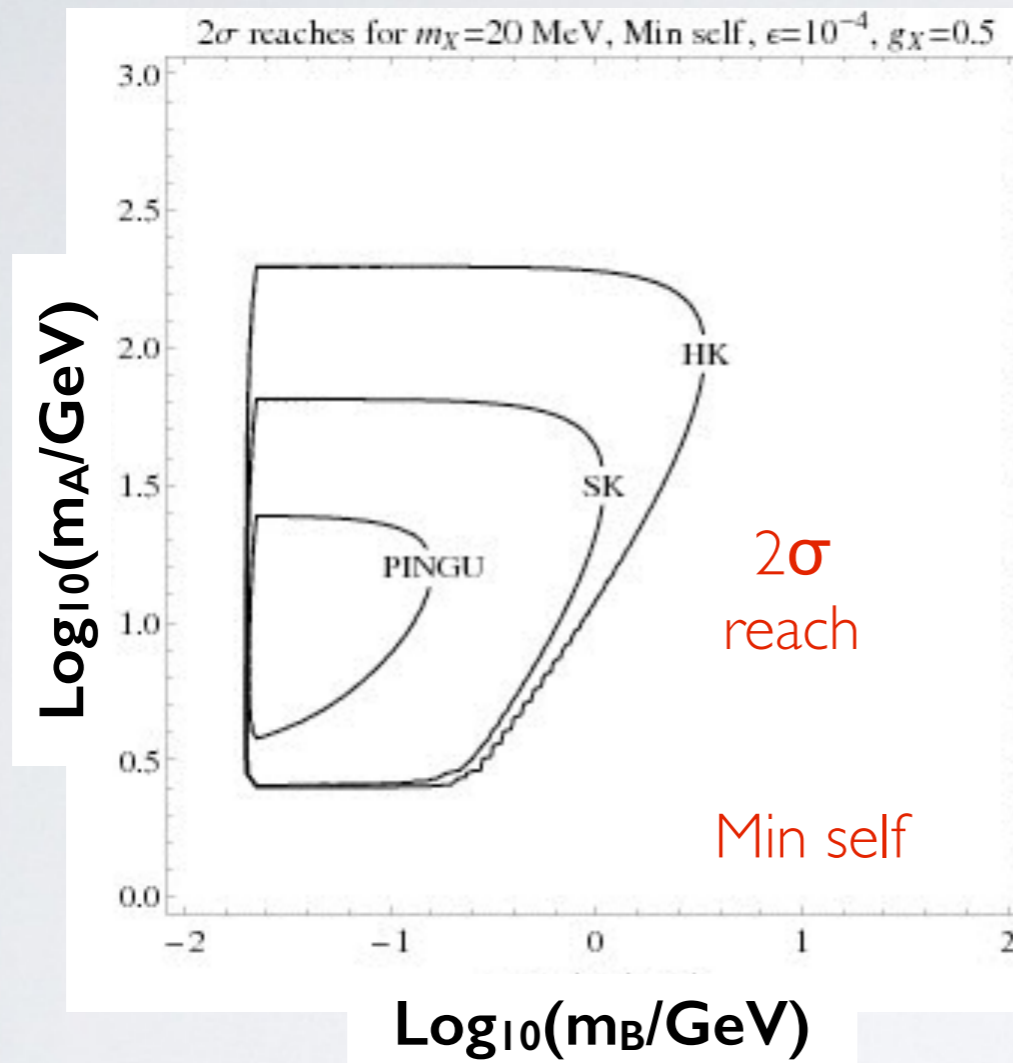
$\text{Log}_{10}(m_A/\text{GeV})$



Experimental Reach

- 2σ sensitivity for 10 years of Data.

Kong, **GM** & Park, 2014.

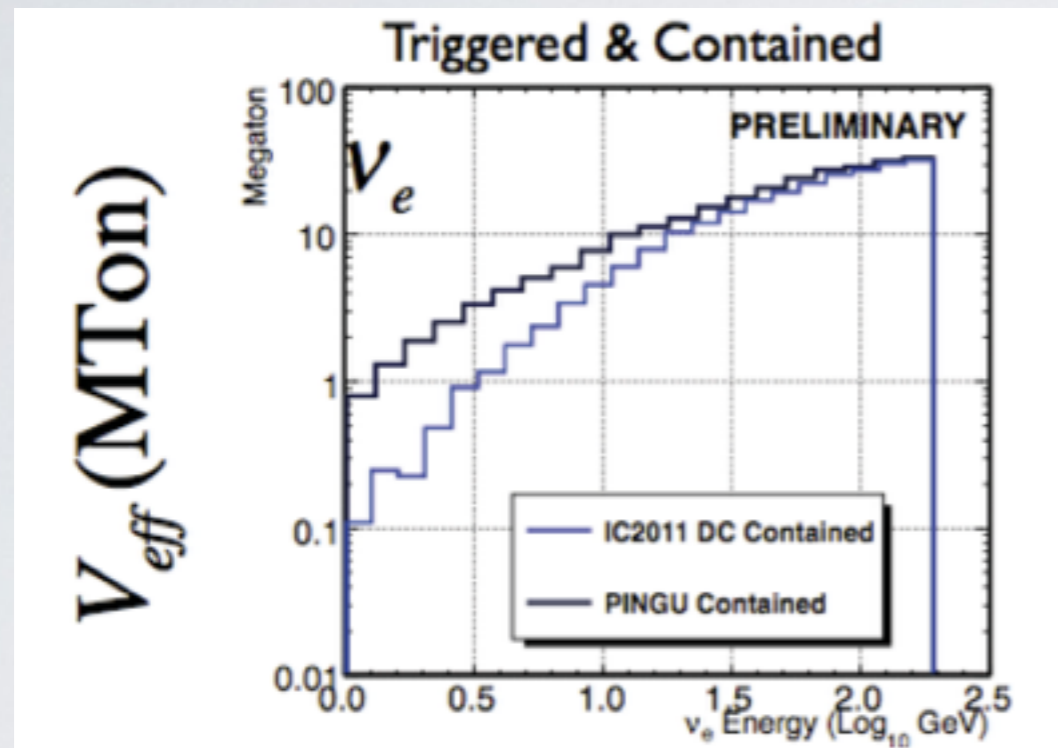


- Left Edge: $m_B > m_X$, Top Edge: number density n_{DM}
- Right Edge: $E_{max} > E_{min}$, Bottom Edge: Evaporation i.e. drop in N_A^{eq}

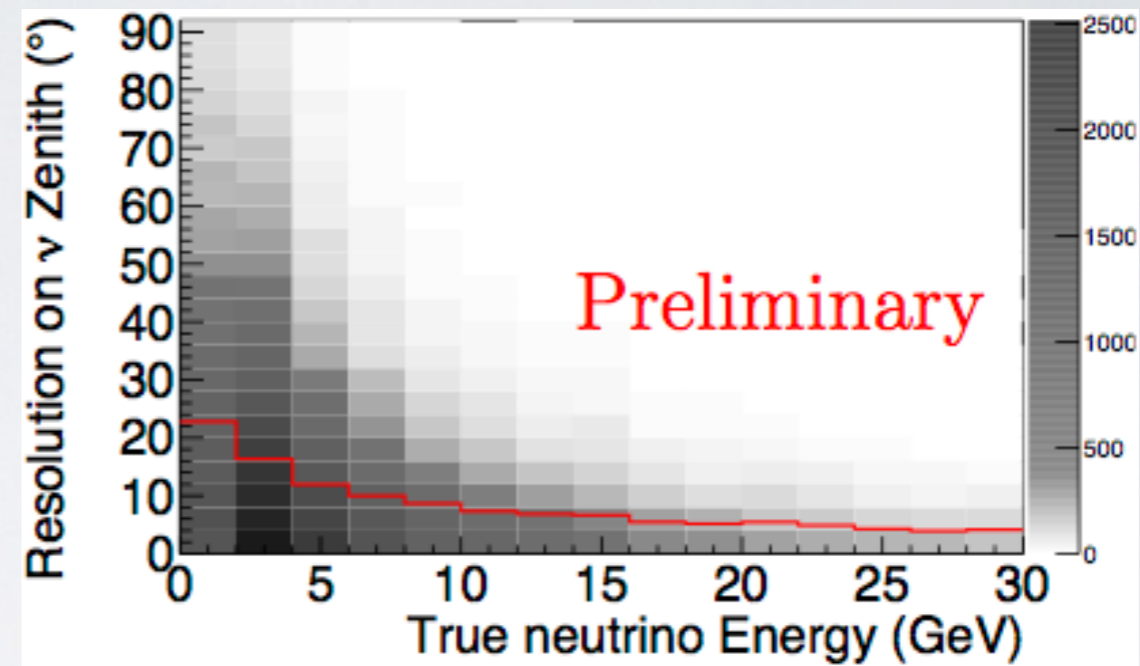
CONCLUSIONS & ONGOING WORK

- DM might be more complicated than previously thought.
- Multi-component scenarios, very well motivated.
- Self-interaction provides insight into several unanswered cosmological questions.
- Self interaction Important \Rightarrow helps enhance flux of Boosted DM.
- Consider Ice-Cube/PINGU:
 - Effective volume $V_{\text{eff}}(E)$.
 - Angular res $\theta_{\text{res}}(E)$.
- Proper modeling of energy loss inside Sun.

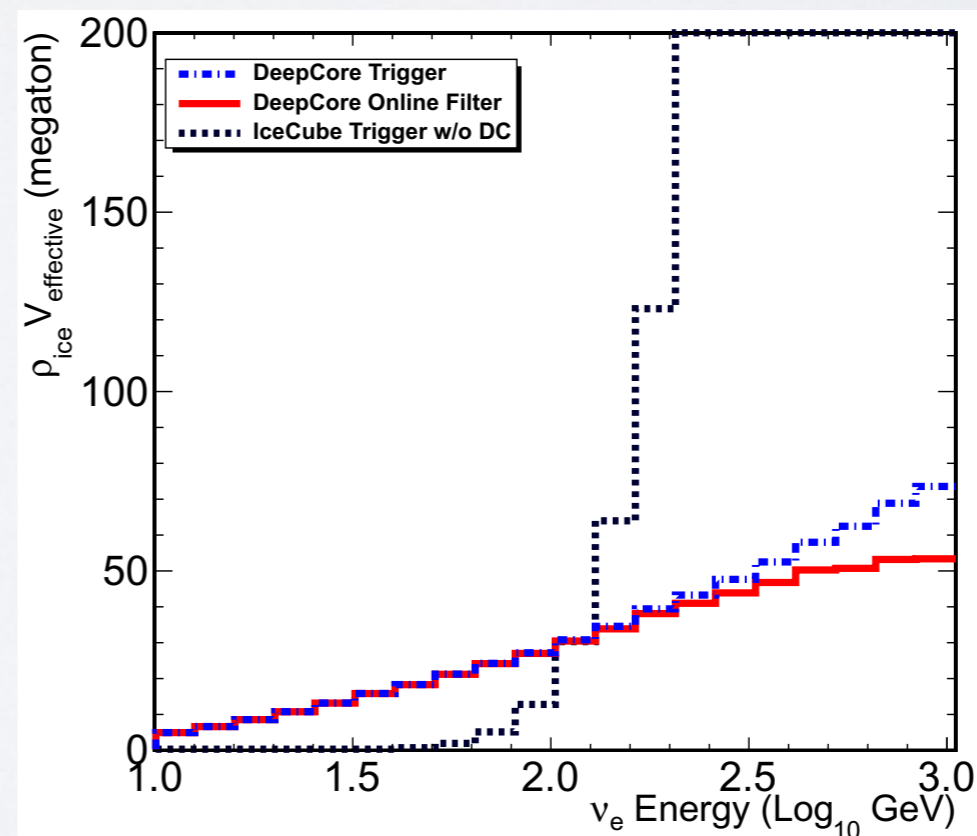
- Consider detection in Ice-Cube deep core and next generation PINGU.
- We consider effective volume and angular resolutions as functions of energy of incoming particle.



Clarke et al [PINGU/Ice-Cube collaboration] 2012



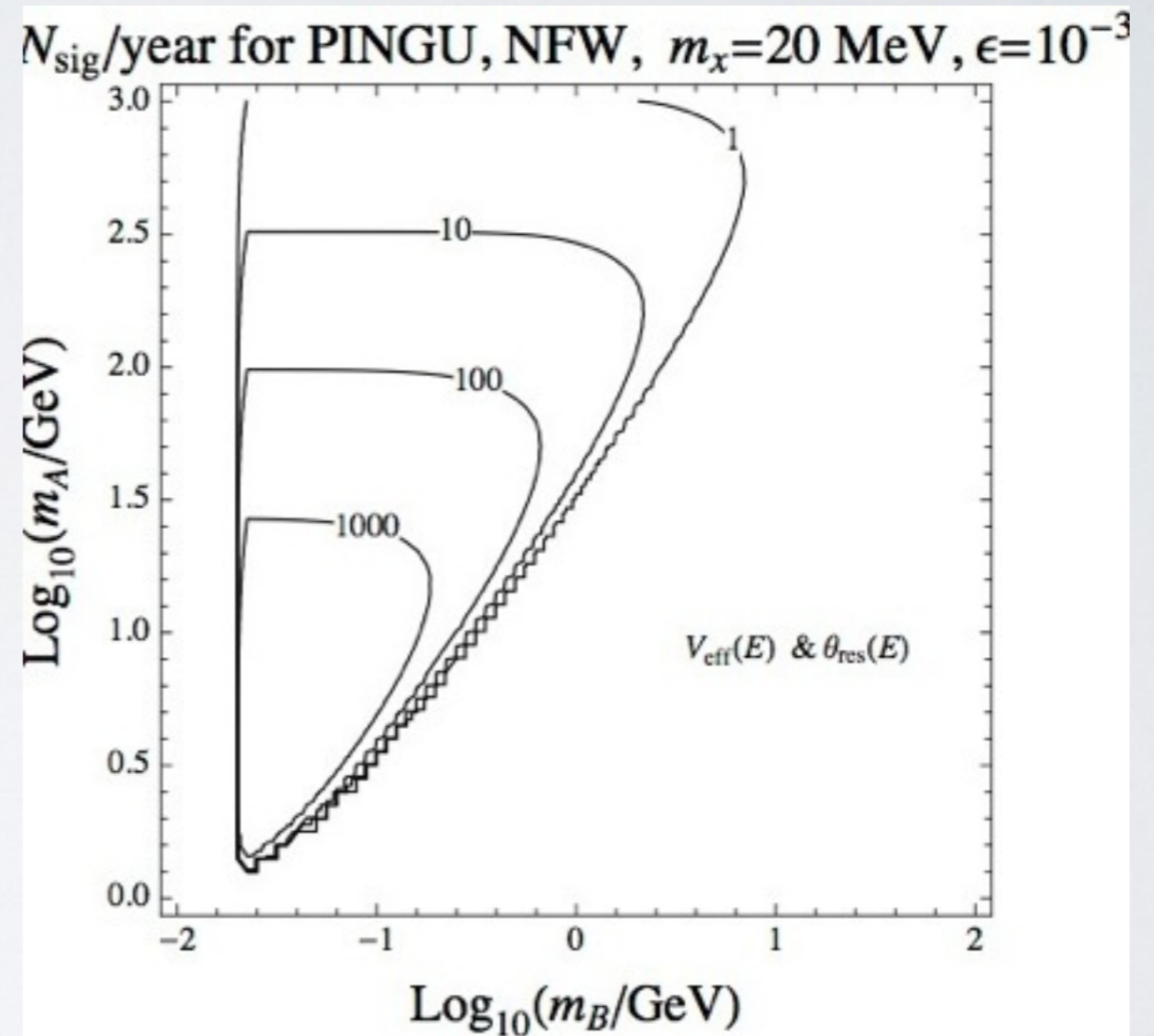
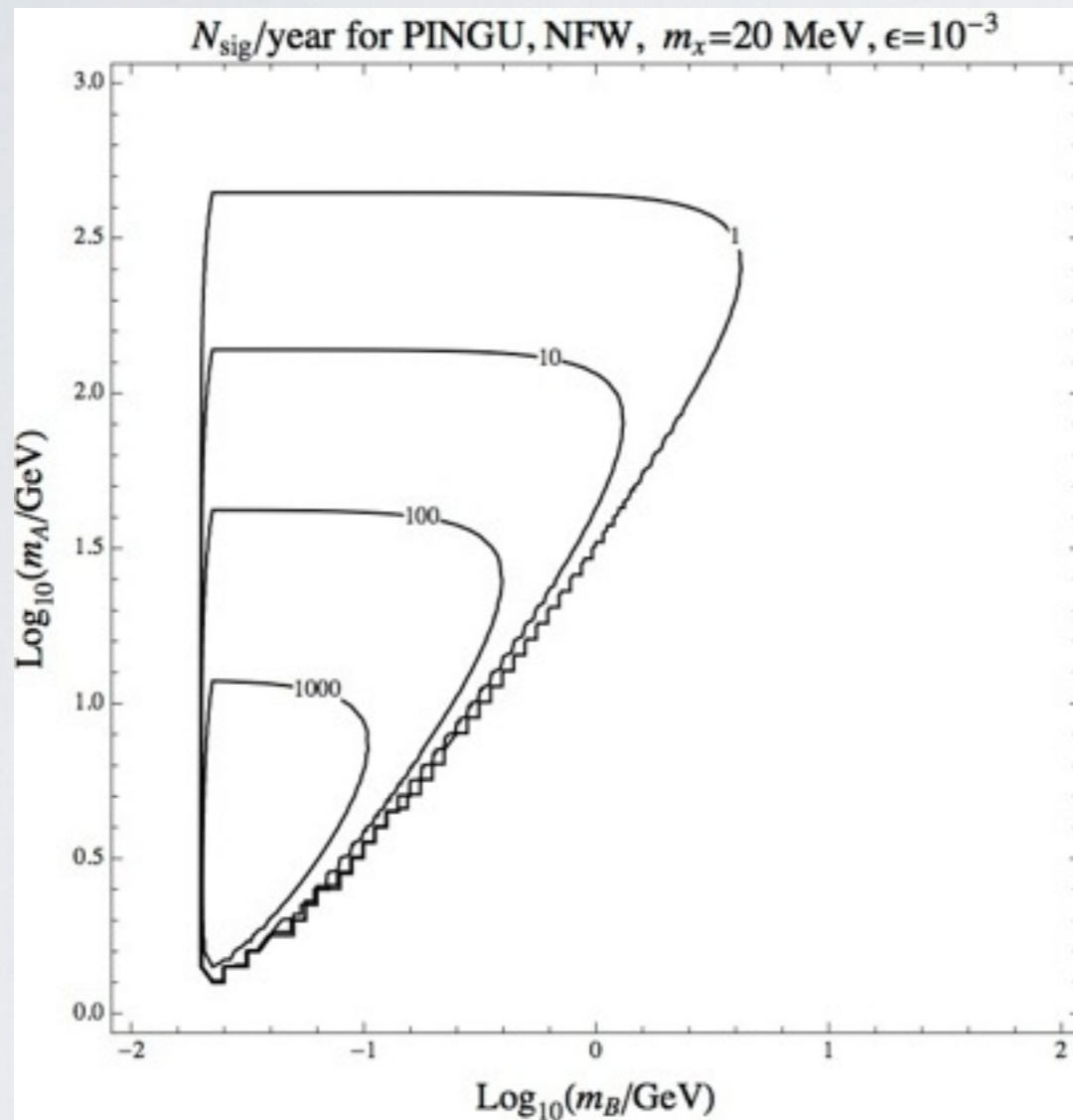
Aartsen et al [PINGU/Ice-Cube collaboration] 2014



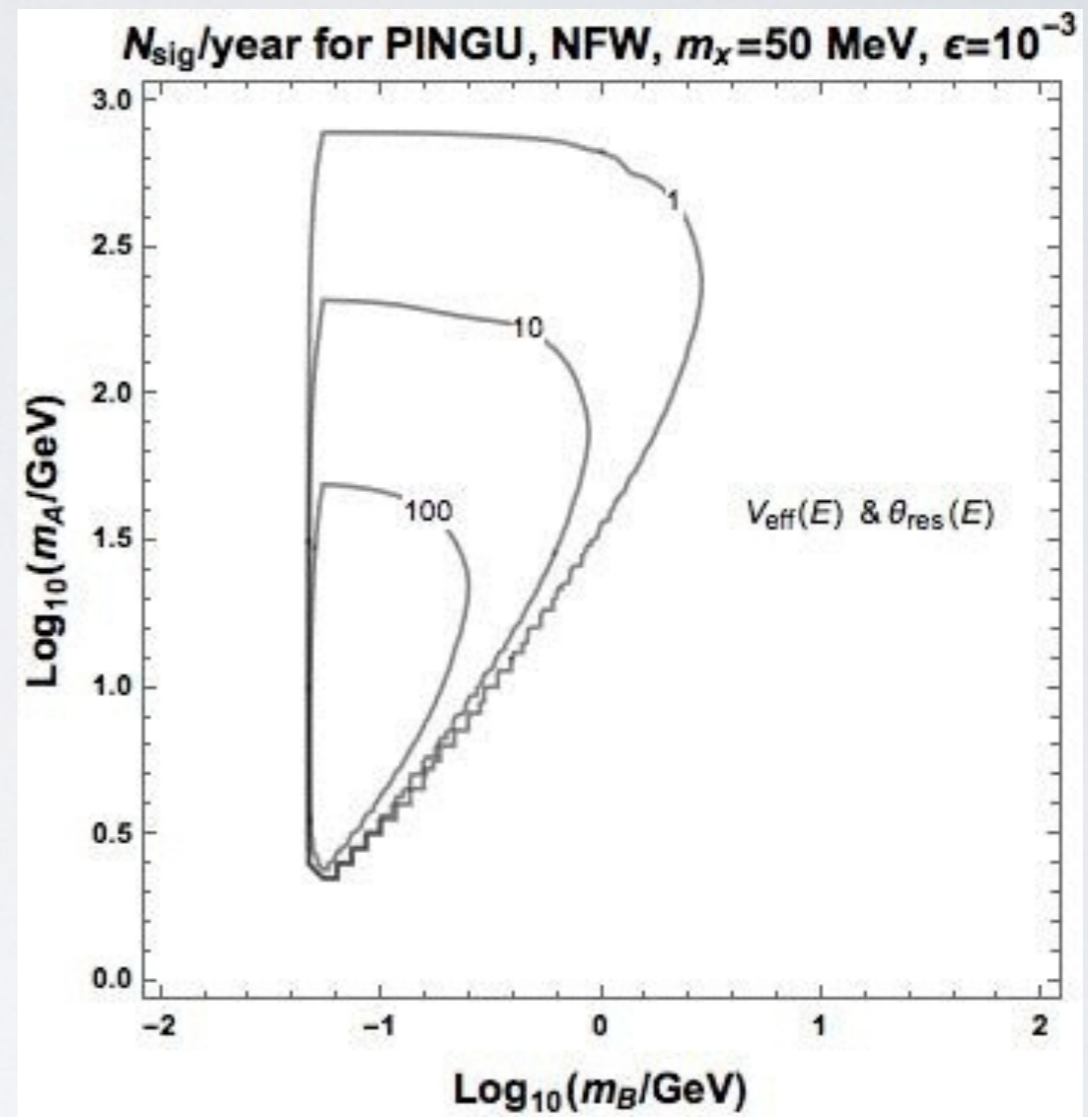
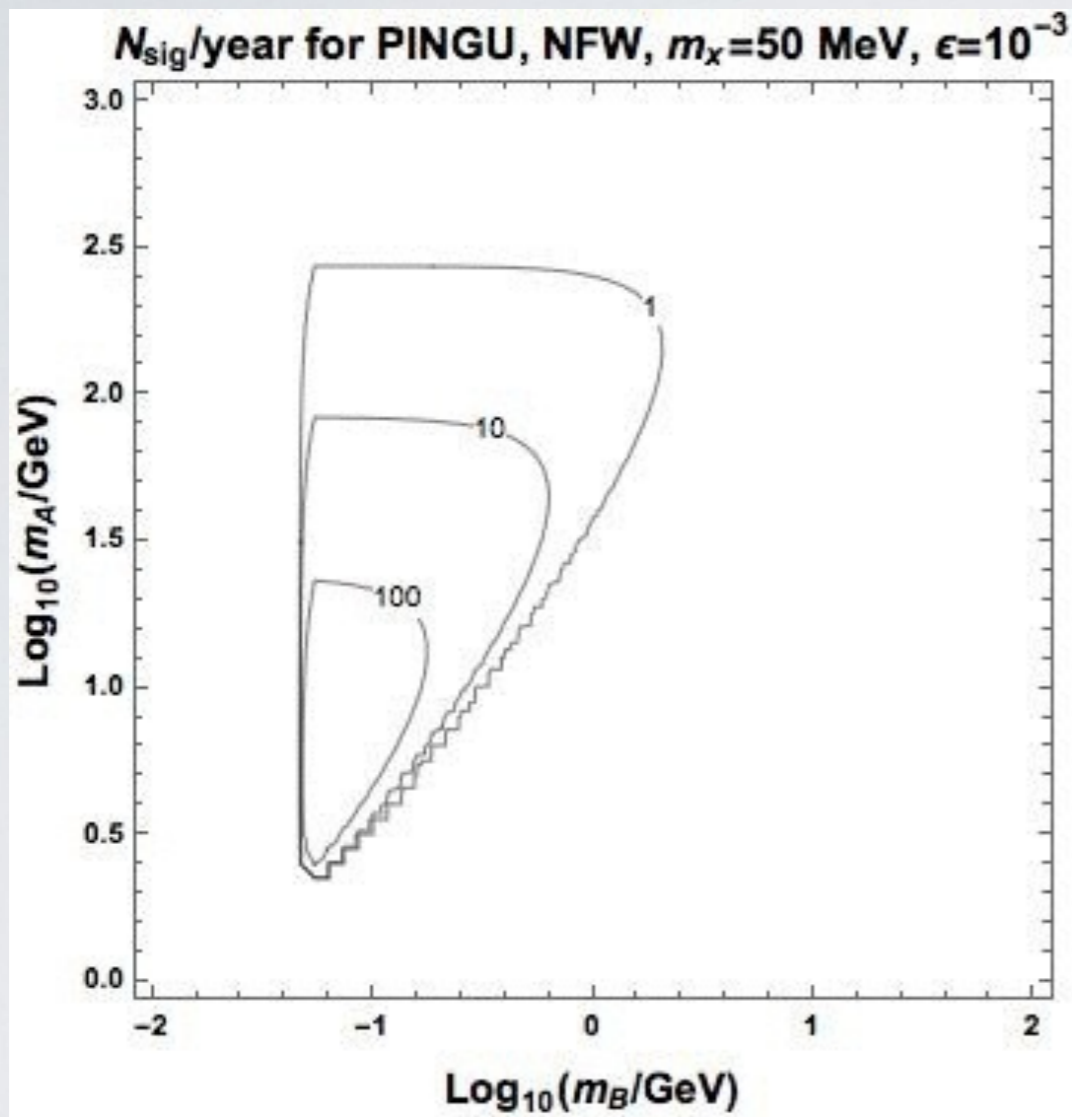
E. K. Ahmedov [arXiv: 1205.7071v1] 2013

Preliminary Results

Boosted DM from the Galactic Center

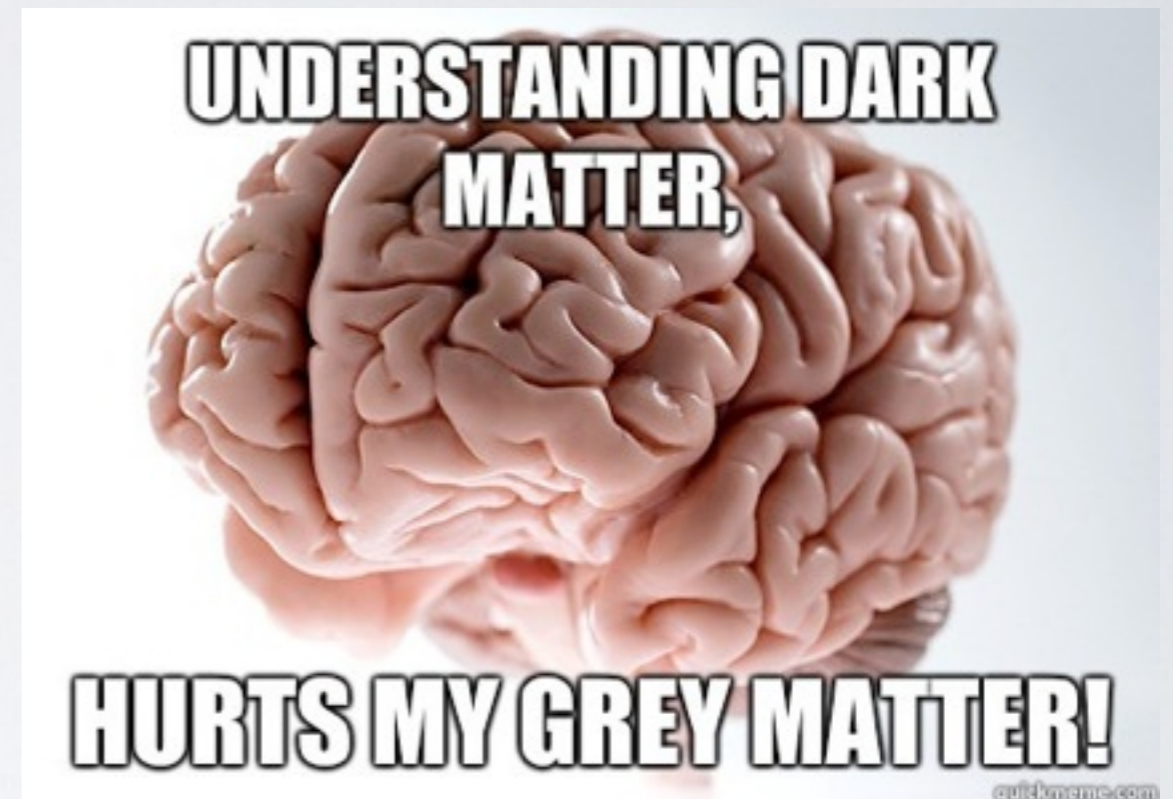


Kong, **G.M** & Park, in Progress.



Kong, **G.M** & Park, in Progress.

THANK YOU



BACK UP

BACKGROUND

- Most background comes from Atmospheric Neutrinos.

most uniform in the sky. $\nu_e n \rightarrow e^- p$

$$N_{BG} = \Delta T \text{ 922/year} \left(\frac{V_{exp}}{2.24 \times 10^4 m^3} \right) \quad \text{For Super-K \& Hyper-K}$$

$$N_{BG} = \Delta T \text{ 14100/year} \left(\frac{V_{exp}}{5 \times 10^5 m^3} \right) \quad \text{For PINGU}$$

- Background reduction dependent on resolution:

$$N_{BG}^{\theta_C} = \frac{1 - \cos \theta_{res}}{2} N_{BG}$$

- For Super-K: $\frac{N_{BG}^{3^\circ}}{\Delta T} = 0.63/\text{year}$, Hyper-K: $\frac{N_{BG}^{3^\circ}}{\Delta T} = 15.8/\text{year}$

- PINGU: $\frac{N_{BG}^{23^\circ}}{\Delta T} = 562/\text{year}$

Event selection

- Boosted DM particles have mono-energetic spectrum, while atmospheric neutrinos have continuous energy spectrum.
- Absence of Muon access, Ψ_B -electron scattering has no Muon access, but Neutrino CC interactions have large Muon access.

$$\nu_\mu n \rightarrow \mu^- p$$

- Multi-ring veto, Ψ_B -electron scattering induces single-ring events while neutrino scattering induces multi-ring events.
- Solar Neutrino veto, Solar neutrinos dominate background so we choose electron Energy > 100 MeV.